The Temporal Nature of Affordance: An Investigation Using EEG and TMS

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Of great importance too is the contribution made by those who participated in the experimental studies, without whom these pages would be blank.

DECLARATION

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ABSTRACT

Affordances play a part in how we prepare to handle objects. Tools and other manipulable objects are said to automatically “afford” various actions depending upon the motor repertoire of the actor. Evidence obtained through behavioural experiments, fMRI, EEG and TMS has proven that this is the case but, as yet, the temporal evolution of affordances has not been fully investigated. Determining the critical time-scale may have significance to patients with brain damage or motor disorders when attempting object manipulation. There are many other factors involved in therapy but it is worth considering that there could be an optimum period of time to view an object before the benefit of an automatic affordance is no longer available. In a series of experiments using the novel approach of positioning the participant’s dominant hand closer to or further from the object being viewed, together with use of three dimensional stimuli, and through application of behavioural assays, TMS pulses and EEG recordings, this research examined temporal properties of affordances in young healthy control subjects. Verification of this motoric activity by EEG led to investigating chronic phase stroke survivors with remaining upper limb deficits and comparing their brain activity with age-matched control participants. As EEG and TMS both have good temporal properties, they are ideal converging methodologies for this kind of investigation. By mapping how affordances develop and dissipate, this work has yielded pure scientific advances in the field of motor decision making. Further, it has resulted in suggestions for future research relating to a possible method to improve rehabilitation interventions for patients who are neurologically impaired by stroke.

Chapter 1 - General Introduction

This thesis has two aims. One is the investigation of naturally occurring affordances, with a particular view towards gathering new information regarding their onset and duration. The second is to determine how or, indeed, whether affordances may play a part in upper limb stroke rehabilitation. A combination of the two strands of investigation provides a contribution to the current knowledge relating to affordances and their possible value in therapeutic interventions. In this chapter, background literature relevant to both strands of investigation is briefly reviewed.

Part 1

To begin the review, literature relating to affordances is discussed. There are now 40 years' worth of studies so this review is limited to investigations around activation of associated brain regions, followed by results of selected behavioural studies. It concludes with recent research regarding monitoring the timing of affordances.

Part 2

Part 1 is followed by a brief summary of the effects of stroke on upper limb function and an assessment of current rehabilitation interventions. Literature is then discussed that relates to trials investigating affordances in rehabilitation.

The themes from part 1 and part 2 are then brought together to lay the groundwork for the following chapters.

1.1 Meaning of the term ‘Affordance’

In his ‘Theory of affordances’ (1977) J.J. Gibson suggested that features of our surroundings including surfaces, inanimate objects and living entities all “afford” actions. The intrinsic properties of everything around us affect our movements and how we navigate our surroundings, avoiding obstacles and interacting with objects. Individual properties or qualities of objects can easily be described, e.g., colour, size and shape but Gibson theorized that naturally occurring affordances did not involve such analysis. Intrinsic properties are perceived without conscious deliberation allowing this theory to be extended to other animals.

The experimental studies in this thesis, and the previous investigations discussed here, do not rigorously adhere to all of Gibson’s theories but maintain and extend the idea that objects prime actions even when those actions are never realised. Being such a vast subject area the following review focusses specifically upon the affordance-like properties of manipulable objects. This is due to their relevance in rehabilitation for loss of upper limb function caused by stroke. The definition of manipulable objects includes items that require the addition of a handle to facilitate grasp as well as those that may be held within the hand. In order to determine the effect of lesions and the role of neuroplasticity on stroke recovery it is necessary to consider the neuronal populations associated with grasping. Since Gibson’s seminal work, many human and animal studies have investigated motor systems and affordances.

1.2 Neural Substrate

Studies of the macaque monkey have led to greater understanding of the functions of visual, motor and visuomotor neurons (Carpaneto et al., 2011; Murata et al., 1997; Rizzolatti, Luppino, & Matelli, 1998; Sakata, Taira, Murata, & Mine, 1995; Vargas-Irwin, Franquemont, Black, & Donoghue, 2015).

Single cell recording in such animals revealed a subset of motor neurons, not only responding to motor activity, i.e. when the monkey reaches to grasp the object, but also when it is passively viewing objects (e.g. Murata et al., 1997; Sakata et al., 1995). This subset of motor neurons was correspondingly named visuomotor neurons. It was concluded that these visuomotor neurons, now more usually called canonical neurons, were responding to the visual features of individual objects, reaffirming the theory that intrinsic visual properties potentiate motor planning. For example Sakata et al. (1995) explored neuronal activity for 4 different objects in 4 different conditions. Each object required a different type of grip or grasp and the conditions were either to manipulate the object in the light or in darkness or to just fixate on the object in the light or in darkness. Individual neurons were recorded in the anterior intraparietal area (AIP) (Figure1.1). Some were mainly activated by hand movement which the authors named motor-dominant and some related to vision and eye-movement, which the authors named visual-dominant. However 25 of the 136 hand movement task-related neurons were also activated in the fixate condition and were named “visual and motor neurons”. In fact, these were found to have a corresponding degree of activity during the fixate conditions in relation to the light and dark manipulate conditions.

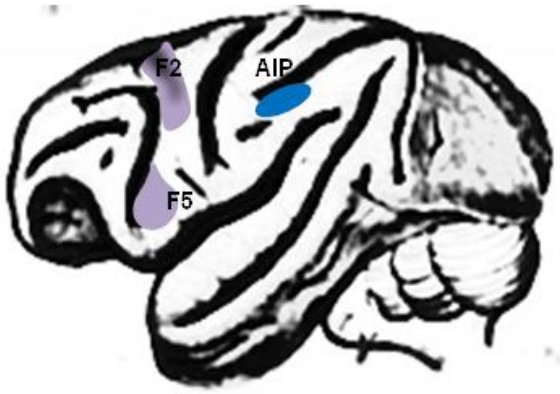


Figure 1.1. Diagram of macaque brain indicating regions F2, F5 and the anterior intraparietal area.

Similar results were also found in studies involving neurons in the ventral pre-motor area F5 (Carpaneto et al., 2011; Murata et al., 1997; Raos, V., Umiltá, M. A., Murata, A., Fogassi, L. and Gallese, 2005). Raos and colleagues also trained monkeys to make movements after a cue in light or in darkness and to carry out a fixate (no movement) condition. Their investigation observed individual neuronal activity in the F5 area, AIP and also the ventro-rostral section of the dorsal pre-motor cortex, area F2vr (Figure 1.1). Area F5 in the monkey brain is generally regarded homologous to the ventral premotor cortex in humans while the AIP is given the same name (the anterior intraparietal area) in humans. In this experiment the monkeys had only to grasp and pull the objects towards them for a set length of time. F5 activity related to choice of grip for grasping but did not relate to individual finger movements. Comparisons were made between the properties of areas F5 and AIP. In F5 no visual-dominant neurons were found such as those in the AIP but in F5 there were more motor neurons. However, in F5 visuomotor neurons showed activity in the object fixate condition as well as prior to movement in the light and dark

movement conditions so it was hypothesized that during the selection of motor schema F5 may play a leading role.

As outlined next, possible affordance activity in different regions of the monkey brain is best considered in the context of the visual processing pathways in primates, including humans, and how they are affected by damage to areas of the brain.

1.3 Ventral and Dorsal Processing Streams

Following early studies in non-human primates, the dual theory of visual processing evolved. Certain “ventral pathway” brain structures in the rhesus monkey were found to be required for object identification. “Dorsal pathway” structures appeared to relate to spatial positioning of objects and visual guidance of motor activity (Mishkin, Ungerleider, & Macko, 1983). From input at the visual cortex, visual processing continues ventrally, towards the medial temporal lobe or dorsally, through the parietal cortex (Figure 1.2).

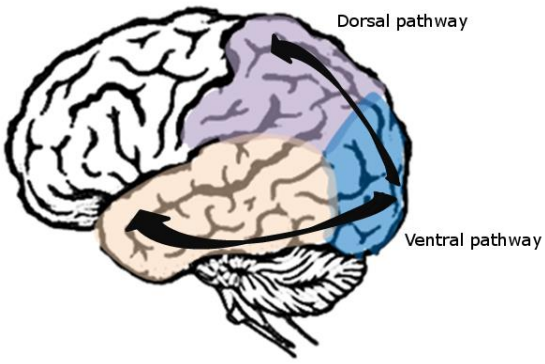


Figure 1.2. Diagram of human brain showing bifurcation of visual processing from visual cortex; arrows indicate dorsal pathway through parietal cortex and ventral pathway through temporal cortex.

Latterly, in humans as well as other primates, the ventral stream has been largely regarded as vision for perception with the dorsal stream regarded as relating vision to physical actions (Goodale & Milner, 1992; Rizzolatti & Matelli, 2003; Xu, Humphreys, Mevorach, & Heinke, 2017). For example, using functional magnetic resonance imaging (fMRI) Cavina-Pratesi, Goodale, & Culham (2007) investigated object processing in the human visual system. They presented subjects with 3D objects and monitored brain activity in dorsal and ventral structures during different tasks. These were either perceptual, relating to pattern or size, or motor tasks where the object had to be grasped or reached without grasping. Results confirmed that there is no single representation of objects in the human visual system. Instead there is both vision for perception and vision for action. The visual perception of objects was mediated by areas in the ventral stream, whereas visual control of action was mediated by areas associated with the AIP in the dorsal steam. However, in a further experiment they found that, to a lesser degree, passive viewing also activated the AIP. Hence these streams should not be considered to each operate to the exclusion of the other, depending on task demands.

Indeed, complementary visual processing from both streams affects our perception *and* guides our actions (Milner & Goodale, 2008; van Polanen & Davare, 2015). This was demonstrated by a patient with ventral stream damage described as the condition ‘visual form agnosia’ (Milner & Goodale, 2008). During various perceptual experiments the dorsal processing stream appeared to be successfully recruited to compensate for the ventral damage. For example, when the task was to pick up a square block positioned adjacent to an

oblong block, sometimes the patient reached towards the oblong but stopped and then picked up the square block. Her ability to verbally discriminate between the shapes was below chance but correct physical responses were above chance. Therefore, information obtained during performance of the action actually assisted her in completing the perceptual task.

In a similar vein, it is worth referring back to the monkey study by Raos and colleagues where they found that F5 showed premotor activity for grasping but that activity did not relate to individual finger movements. Could ventral neurons be recruited to assist dorsal stream processing when objects have complex shapes and/or textures? Very recently van Polanen and Davare (2015) suggested just that; as complexity of movement increases, requiring fractional movement of each individual finger, ventral areas are recruited for sensorimotor assessment of object properties to aid the dorsal stream. This would imply that, although the ventral structures alone may not be effective for finely skilled finger movements, as in the afore-mentioned monkey experiment, the relay of information between ventral and dorsal stream structures allows for complex, skilled movements. Such interactions may be important in preserving or improving fine motor skills in those affected by stroke where damage has been caused in dorsal and/or ventral structures. Fuller implications for areas of infarct and neuroplasticity will be discussed later. The review now turns to evidence of affordances in behavioural experiments.

1.4 Motor Planning

In the exploration of affordances a number of behavioural human studies have focused on prime-induced conflict in motor planning (Grèzes, Tucker, Armony, Ellis, & Passingham, 2003; Tucker & Ellis, 2001).

In one variant of this type of procedure, participants are required to respond with a specific grip for a group of objects, e.g., a forefinger and thumb precision grip for natural objects and a whole-hand power grip for man-made objects, irrespective of the size of the object or whether or not that type of grip would normally be used. (Figure 1.3 gives examples for a study of this type). Reaction times are typically found to be greater for incongruent trials (e.g. a power grip

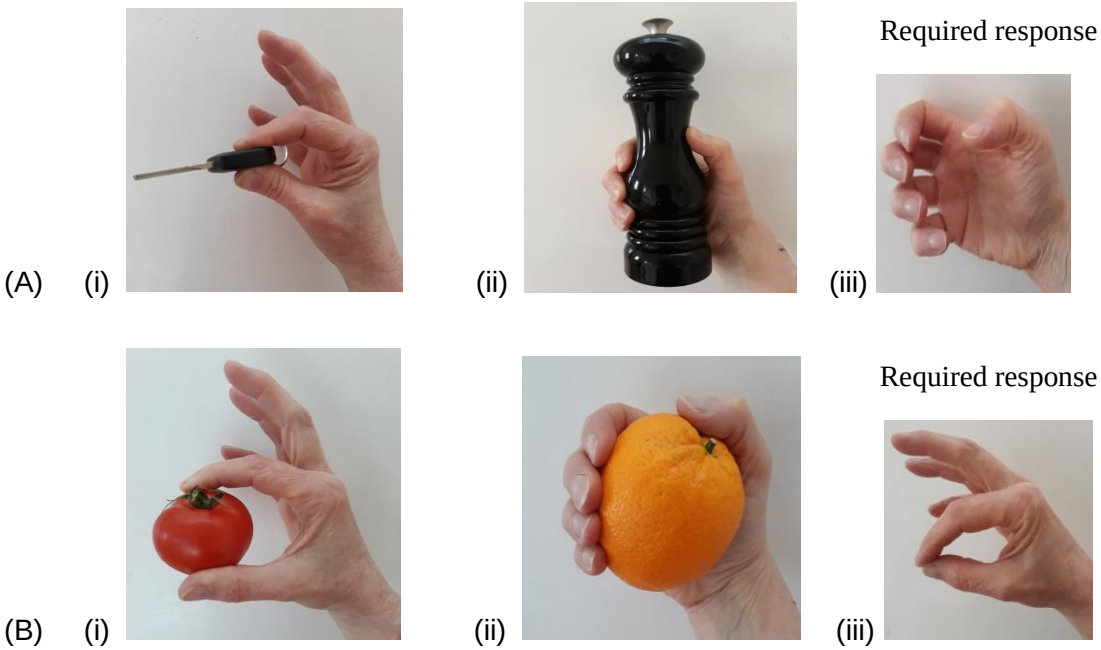


Figure 1.3 (A) Example of man-made objects being held in (i) precision grip and (ii) power grip. (iii) power grip response would be incongruent for the key in (i) but congruent for the peppermill in (ii). (B) Example of natural objects held in (i) precision grip and (ii) power grip. (iii) precision grip response would be congruent for the tomato in (i) but incongruent for orange in (ii)

made in response to a man-made object that would normally be held in a precision grip) presumably due to conflict between the action afforded by the object, especially its size, and the response required for the task. Tucker and Ellis (2001) pioneered this behavioural approach, while fMRI monitoring by Grèzes et al. (2003) correlated brain activity with behavioural results, revealing greater left-hemisphere activity in congruent trials. Particular ventral or dorsal stream activity was not determined but notable regional activity occurred in the premotor cortex, the inferior frontal sulcus, superior temporal sulcus, anterior parietal cortex and superior parietal lobe.

Similar activations were observed by Creem-Regehr and Lee (2005) and Vingerhoets (2008). In the former study when participants viewed tools compared to geometric three-dimensional images (such as a cylinder or a cone), the tools produced activation in lateral posterior temporal cortex, posterior parietal cortex and premotor cortex. The geometric shapes activated only the left inferior temporal gyrus. Vingerhoets (2008) showed his volunteers familiar and unfamiliar tools and also non-objects in the form of abstract shapes. Both the familiar and unfamiliar tools activated predominantly left premotor, posterior parietal and temporo-occipital areas with generally greater activity for the more familiar tools. These two studies concluded that tools produce stronger affordances, partly due to the observer's familiarity with using such tools, and that shapes without particular functional relevance produced little evidence of affordance.

fMRI during action observation tasks has recently provided detailed evidence of brain regions activated specifically when attention has been directed towards

the object in the sequence (Nicholson, Roser, & Bach, 2017). Participants pressed a button when they identified consecutive repetitions in video sequences. They focussed on one of three different conditions; goal, movement or object, while ignoring repetitions relating to the other two conditions. A goal was, for example, to have a door opened, whether by the different possible actions of knocking or pressing a door-bell. An example of movement repetition was turning a dial on a shower and turning a dial on a microwave oven, whereas object repetition was, for example, a teaspoon used to stir and a teaspoon used for distributing sugar. Left hemisphere prefrontal and middle temporal regions showed more activation during the object task than the movement task and also during goal compared to movement tasks. Results highlighted that it may be objects rather than motor information that initialize identification of the goal related to an action. The strong left fronto-temporal activity in this study differs slightly from the earlier findings of additional parietal areas activated by familiar tools, even though the objects used by Nicholson et al. (2017) could also be described as tools. Further investigation may clarify these differences but of importance for this thesis is the finding that it may be the object rather than the movement that holds the key in action observation treatment. As action observation is a common feature of stroke rehabilitation (for example, see Buccino (2014)), the affordance properties of an object may play a greater part in this rehabilitative method than previously thought. Therapies which may benefit from knowledge of affordances will be discussed further in the second part of this literature review.

The affordance properties of tools are now well-documented (Kellenbach, Brett, & Patterson, 1984; Nicholson et al., 2017; Osiurak et al., 2009; Righi, Orlando,

& Marzi, 2014; Valyear, Cavina-Pratesi, Stiglick, & Culham, 2007) so much so that tool affordance knowledge is being used in robotic learning technology, (e.g. Gonçalves, Saponaro, Jamone, & Bernardino, 2014).

By contrast, Creem-Regehr and Lee (2005) suggested that unlike tools, plain geometric shapes were either not implicitly interpreted as graspable or lacked functional specificity tied to any action to accomplish a useful goal. Vingerhoets (2008) argued that such geometric shapes not only have reduced functionality but also hold limited visual properties to make them tool-like and invite manipulation. While this is a valid explanation for basic geometric shapes, it could be argued that manipulative objects need not be tools to have an affordance effect. Even being "tool-like" is not an entirely relevant feature for objects to afford actions. In fact, the natural objects which effected the faster response times in the classic Tucker and Ellis (2001) study of motor priming were all forms of food; items such as a grape, a chilli and various nuts for the small objects and a banana, a swede and a mango as examples of large objects. Tools are undeniably beneficial in eliciting affordances but other manipulable objects, whether natural items, for example foods, grasses, pine cones, feathers, and sea shells, or manmade ones, such as ornamental figurines or jewellery, may still produce affordances. The importance of these other items is that a variety of objects, as well as tools to aid daily living, are already used to assist rehabilitation and improve upper limb function after neurological damage. The relevance to this thesis is therefore to investigate different types of objects that may be useful in eliciting affordances in stroke rehabilitation. It may not always be entirely the functionality of the object but sometimes its familiarity that triggers affordance-like brain activity. This

research was intended to gain insights into the temporal nature of affordance and to consider how affordances may prompt movement in patients who have upper limb deficits. In therapeutic interventions, if there is an affordance effect, the patient's ability to interact with an object may depend on the length of time that object is presented.

1.5 Studies Observing the Time-course of Affordances

A few recent studies have used electroencephalograpy (EEG) (Goslin, Dixon, Fischer, Cangelosi, & Ellis, 2012; Proverbio, 2012; Proverbio, Adorni, & D'Aniello, 2011) and transcranial magnetic stimulation (TMS) (Buccino, Sato, Cattaneo, Rodà, & Riggio, 2009; Franca et al., 2012; Makris, Hadar, & Yarrow, 2011) to ascertain time-courses of affordances. In one EEG study volunteers pressed a button with one hand or the other depending on the category of the object presented, either tools or kitchen utensils (Goslin et al., 2012). Although this categorisation was independent from the positioning of the object's handle, congruent responses were produced more quickly; that is, faster right hand responses when the handle was directed to the right and faster left hand responses when the handle was positioned toward the left. In relation to the above discussion about tools and other objects, it is interesting that responses were found to be faster for tools compared to kitchen utensils. There was no evidence that participants would be more familiar with tools than kitchen utensils and functionality would have remained similar for both categories of object. Lateralised readiness potentials, which are known to index motor preparation, revealed greater negativity in the contralateral hemisphere to the hand preparing to press the button for congruent trials than for incongruent

trials. This was noticeable only during the 100ms to 200ms after stimulus onset suggesting early visual object processing directly linked with motor priming.

When participants only passively viewed stimuli, Proverbio et al. (2011) found greater negative anterior activity at 210ms to 270ms after stimulus onset and greater positive centro-parietal activity at 550ms to 600ms when participants passively viewed tools compared to non-tools. There was increased activity for the non-tools at 750ms to 850ms. The authors attribute these differences to the presence/absence of affordances, although one slightly confounding factor in this study was that the category of tools included non-manipulable items, such as a staircase and also a bicycle which might facilitate affordances relating to both upper and lower limbs.

TMS studies have also linked viewing pictures of objects with affording the appropriate action. Motor evoked potentials (MEPs) recorded from electrodes placed over muscles on the hand are a sensitive index of preparation for movement. Evidence was observed in larger MEPs for muscles associated with the compatible action for handles orientated to facilitate grasp, when TMS pulses were delivered to the contralateral motor cortex 200ms after stimulus onset (Buccino et al., 2009). Similarly, with TMS pulses delivered at 300ms and 450ms after onset (but not later) larger MEPs were observed when object size was compatible with type of grip; that is, larger MEPs from the abductor digiti minimi (ADM) muscle (involved in power grip) when viewing large objects and larger MEPs from the first dorsal interrosseous (FDI) muscle (involved in precision grip) when viewing small objects (Makris et al., 2011; Makris, Hadar, & Yarrow, 2013).

Summarising these studies, there was a broad range of affordance-related changes in brain activation between 100ms and 600ms in the two afore-mentioned EEG studies and between 200ms and 450ms after stimulus onset observed with TMS. Methods differed slightly with a response required for the Goslin et al. (2012) study, but just passive viewing for all the others. In the 2013 TMS experiment (Makris et al., 2013), actual objects were presented rather than two dimensional pictures which may have relevance on the timing of the MEP effects. The large variance in the temporal extent of these possible affordances shows that further investigation is necessary and experiments detailed in following Chapters contribute to knowledge of timing of object-evoked motor-related brain activity.

This literature review now addresses the second thesis question regarding the possibility of affordances being used in stroke therapy.

1.6 Stroke and Upper Limb Deficits

According to The Stroke Association ‘State of the Nation Stroke Statistics - January 2017’ stroke occurs more than 100,000 times a year in the UK. It is one of the largest causes of disability with two-thirds of survivors leaving hospital with a disability. There are over 1.2 million stroke survivors in the UK with NHS and social care costing around £1.7 billion a year in England alone.

Disability after stroke varies enormously and among other deficits may include difficulties in swallowing and speech, hemiplegia, loss of function in upper or

lower limbs, poor trunk control, visual difficulties and fatigue. For this thesis, the area of interest is the recovery of upper limb function and the possible benefit of interventions where use is made of naturally occurring affordances. However, therapy has to address many types of deficits:

(Adapted from Stroke Association UK Factsheet 33 and Upper limb management after stroke factsheet published for Stroke Foundation – Australia)

Weakness. The whole arm may suffer complete paralysis or the shoulder, elbow, wrist or hand may be weak.

Planning or coordinating problems. Due to varying degrees of apraxia, there may be difficulty planning arm movements. There may be poor coordination causing slowness of arm movements or making movements appear clumsy.

Changes in the muscle-tone. Hypertonia, or spasticity, is the stiffening of muscles whereas hypotonia is low muscle tone.

Shoulder subluxation. Changes in the muscle may cause the arm to sit slightly lower in the shoulder socket.

Contracture. Muscles stiffness can cause them to become permanently shorter which can result in a joint becoming fixed in one position.

Swelling. Lack of movement may cause fluid to build up (oedema).

Pain. Changes in the muscles, subluxation and contracture can cause pain. Changes in sensation can also cause pain.

Theoretically, therapy incorporating object affordances would be most likely to help patients with planning or coordination problems. Apraxia is the inability to perform an action even when being physically able, with normal muscle tone, and consciously desiring to do so. The main clinical classifications are conceptual, ideomotor and ideational apraxia (Canzano et al., 2016; Goldmann Gross, 2008; Koski, Iacoboni, & Mazziotta, 2002). Conceptual apraxia is basically the inability to select the correct tool for an action although the patient may be able to correctly carry out the action. Ideomotor apraxia describes

inability to make the correct physical response when given a verbal command or when given a physical cue, such as a tool to be used. Although the patient may even select the correct tool, the manner of its use is compromised, resulting in a severe disruption of activities of daily living (ADL). For example, the patient may attempt to brush their hair with the flat part of the brush rather than the bristles. Therefore, in stroke rehabilitation sessions for both of these types of apraxia an Occupational Therapist may ask the patient to hand objects to them as well as carry out a task with that object. Ideational apraxia is described as lack of ability to carry out a sequential task. While grasping an object and using it correctly might not be challenged, certain activities of daily living requiring consecutive steps such as dressing or making a cup of tea may be beyond the stroke survivor's capabilities. It is generally thought that bilateral damage to tempoparietal areas results in conceptual apraxia whereas left parietofrontal damage is likely to cause ideomotor apraxia. Patients with ideational apraxia generally have a larger region of the brain affected and possibly depletion of higher executive function.

Middle cerebral artery stroke is the most common type to cause upper limb apraxia. This artery, supplied by the internal carotid artery, passes through the temporal sulcus and branches out to supply most of the lateral hemisphere. Interruption of blood supply to the pre-motor cortex as well as parietal areas, inferior frontal and superior temporal sulci may cause various degrees of apraxia. If the infarct covers a large area, this is more likely to cause ideational apraxia. The middle cerebral artery also supplies subcortical areas such as the caudate nucleus, putamen, internal capsule and the globus palladus. All cortical areas involved in motor planning and execution project to the caudate

nucleus and putamen and then to the globus palladus. Lesion in any of these areas is very common; hence many stroke patients suffer diminished upper limb coordination and require rehabilitative interventions.

1.7 Varying Rehabilitation Practices

A great deal of research is being carried out to improve outcomes after stroke but there is also extreme variability of facilities and therapy offered throughout the U.K. National Health Service and, indeed, worldwide (Pollock et al., 2014; Reuter et al., 2016; Ward, Kelly, & Brander, 2015).

Neural plasticity is important in recovery after stroke (see, for example, Dimyan & Cohen, 2011; Hosp & Luft, 2011; Swayne, Rothwell, Ward, & Greenwood, 2008; Ward & Cohen, 2009). Histological evidence from rodent models suggesting that cortical dendritic branching and axonal growth are paralleled by functional recovery (Biernaskie, 2004; Biernaskie & Corbett, 2001; Okabe et al., 2017) has been confirmed in human recovery through neuroimaging (Swayne et al., 2008; Ward, Brown, Thompson, & Frackowiak, 2003). There is a general belief that the sooner rehabilitative training begins after stroke, the greater the cortical reorganisation and improvements in sensorimotor function (for example, Ward et al., 2015). Comparing the timing of initial task-specific training of forelimb in rodent models has shown improved functional outcomes when started earlier after lesioning rather than later (Biernaskie, 2004; Biernaskie and Corbett, 2001; Hosp and Luft, 2011; Okabe et al., 2017). However, initial rehabilitation in the acute phase after stroke varies for a number of reasons, not least depending on available resources. Reuter et al. (2016) undertook a review

of more than 105,000 patients on the Baden-Wuerttemberg stroke registry over nearly 5 years from January 2008 to December 2012. Similarly to Ward et al. (2015) they found that, overall, outcomes were most favourable the earlier and more intensive the therapy. Rather alarmingly, they also found that initially if the patient had either a very good or very unfavourable recovery prognosis, they were less likely to receive specialised rehabilitation.

It appeared that treatment decisions made by staff reflected attempts to optimize available resources. The review noted that less occupational therapy and speech therapy occurred than physiotherapy. It also referred to the somewhat contradictory findings of Bernhardt (2015) (on behalf of the AVERT Trial Collaboration Group) who undertook a study from July 2006 to October 2014 of 2104 participants in the acute stage of stroke (the AVERT study). Those who were assigned to very early mobilisation started mobilisation within 24 hours of cerebral incident, receiving much higher dose treatment compared to the usual care group. Around 50% in the usual care group were also mobilised within 24 hours after stroke. Most of the other 50% were mobilised after 24 hours but within 48 hours. The authors hypothesised that at 3 months those in the former group would have better functional recovery with accelerated walking and fewer complications due to immobility. However, at 3 months, favourable outcomes were reversed with overall better functional recovery and lower mortality rate in the usual care group, although mortality rate differences were not statistically significant. Sub-group analysis signalled that patients with severe stroke and intracerebral haemorrhage had reduced likelihood of favourable outcome if they received the very early mobilisation protocol. In correspondence to The Lancet regarding findings of the AVERT

study, Barer, & Watkins, (2015) suggested that the haemodynamic changes in blood flow when changing from supine to head raised position could result in adverse effects on the ischemic brain for severe stroke.

Apart from the inherent variability in start time and dose intensity of rehabilitative interventions there also appears to be an ongoing debate regarding safety and effectiveness of very early mobilisation. If the danger arises from placing the patient in an upright position then simple upper-limb activity whilst in a supine position could negate that danger. Early treatments conducted while the patient is supine have not been reviewed. This is an area where upper limb therapies, incorporating any benefits from affordances, are less likely to have detrimental consequences.

According to Ward et al. (2015) the current amount of time being spent on upper limb activities with patients in the acute phase after stroke is too low.

Pollock et al. (2014) synthesised 40 systematic reviews of randomized controlled trials (RCTs) to produce an overview of interventions provided to improve upper limb function after stroke. The report concluded that by June 2013 there was no high-quality evidence that any interventions were being routinely used in upper limb stroke rehabilitation. Moderate-quality evidence suggested efficacy of a number of interventions but there was insufficient evidence to show which were the most beneficial. These were mental practice, mirror therapy, constraint-induced movement therapy, interventions for sensory impairment, virtual reality and relatively high dose repetitive task practice. There were recommendations for randomized clinical trials of all of the above-

mentioned interventions as part of a wider range, as diverse as reach-to-grasp exercise, repetitive transcranial magnetic stimulation (rTMS) and music therapy.

Of interest here is the possible effectiveness of affordances in conjunction with, for example, reach-to-grasp exercises, action observation and repetitive task practice and in virtual reality platforms.

1.8 Affordances in Therapy?

Using objects with appropriate properties, e.g. their functional relevance and their spatial position, has been shown to produce better movement in patients with a range of motor difficulties originating from neurological conditions such as Parkinson' Disease (PD) (Galpin, Tipper, Dick, & Poliakoff, 2011; Poliakoff, Galpin, Dick, Moore, & Tipper, 2007) and cerebral palsy (Volman, Wijnroks, & Vermeer, 2002) as well as stroke (Mizelle & Wheaton, 2014; Wisneski & Johnson, 2007). This suggests that affordances may still be being generated in patients, and thus might contribute to training regimens influencing behaviour through neuroplasticity.

For example, for 12 children with mild or moderate cerebral palsy, object affordances in a functional task elicited improved speed and smoother control of the hemiplegic arm in reaching movements compared to semi-functional and non-functional tasks (Volman et al., 2002). For the functional task, the children were told to reach to press a switch to turn on a light. In the semi-functional task they were just told to reach to press the switch. For this task the light was disconnected. In the non-functional task they were told to reach to a marker.

The functional task produced the best movement results but a more pronounced difference was found between speed and fluidity of movement in the semi-functional compared to the non-functional condition. There is no doubt that the motivationally meaningful stimulus of a switch to produce light has an effect on movement planning and control but here it would appear that motor performance was more strongly impacted by the object availability rather than the goal. Interestingly, a similar approach was discussed by Mizelle and Wheaton (2010). They supported the theory that knowledge of the appropriate use of a tool is embodied in our cognitive processes thereby allowing us the correct grip and manner of use of that tool at a future date. Perhaps this is not the case with ideomotor apraxia but grounded cognition may have a part to play in assisting some stroke survivors with object grasping and manipulation. Their article suggested that further exploration of affordances in respect of grounded cognition might provide insight into the neuroscience of the different types of apraxia.

Affordance-like motor priming might have a different effect in some patient groups. Visuomotor priming from action-relevant stimuli may be altered by Parkinson's Disease (PD) (Galpin et al., 2011; Poliakoff et al., 2007). Galpin et al. (2011) carried out an investigation comparing spatial and affordance effects in both healthy controls and PD patients. The affordance stimulus was a door handle while the spatial stimulus was made of six shaded spheres positioned in a line making a similar shape as the door handle. Participants pressed a button with their left or right index finger, depending on whether the stimulus was blue or green and ignoring the direction of the handle. There were three stimulus onset asynchronies (SOAs), 0ms, 500ms and 1000ms. The control participants

showed a greater compatibility effect for affordance stimuli than spatial stimuli at 500ms only. The authors believed that the control participants' response times were influenced by action-relevance *facilitating* responses to the *compatible* stimuli whereas, conversely, the spatial location *slowed* responses to *incompatible* stimuli. Patients showed no difference between conditions at any SOA. In fact, it appeared that the patients' response times were, if anything, *facilitated* for *compatible* stimuli in both conditions. It was believed that normal affordances were available to the Parkinson's Disease patients but also for them, due to reduced motor inhibition, the spatial stimuli of spheres in a line may have held strong affordance-like properties.

Recent studies with chronic stroke patients (Alt Murphy, Baniña, & Levin, 2017; Randerath et al., 2018; Randerath, Goldenberg, Spijkers, Li, & Hermsdörfer, 2011) have considered the value of affordance in those whose upper limb deficits do not include a diagnosis of apraxia. In fact, in a goal-directed affordance experiment by Alt Murphy et al. (2017) diagnosis of apraxia was part of the exclusion criteria. They carried out a grasp-height experiment where particular observations were made as to the grasp position on a vertical bar-shaped object (bathroom plunger) when it was moved from a platform to another, height-adjustable platform. In such experiments there is a grasp-height effect; participants tend to grasp the plunger handle closer to the top when it is to be placed on a low platform and closer to the base when it is to be placed on a higher platform.

Healthy controls using dominant right and non-dominant left hand and stroke patients using paretic and non-paretic limb all displayed this grasp-height effect.

However, patients with visuo-perceptual defects showed this result to a lesser extent, (e.g. using a lower grasp height when moving the plunger to the lowest platform). Most interestingly this was the case even for their non-affected limb. With motor deficits ruled out, this indicates that visual perception affects aspects of daily living not just confined to the limb with loss of function. The authors suggested that to develop the ability to modulate grasp according to object affordance, rehabilitation should also include practising reaching movements to different locations of the arm workspace. Like in the grasp-height task, affordance properties may be more meaningful where there is a final goal, but especially where there is a relationship between objects within that goal.

Randerath et al. (2011) investigated three conditions: pantomime action, demonstration of tool use and the tool's actual use with a recipient object. The tools were a hammer with recipient object of nails and a ladle to scoop soup from a bowl to a soup plate. Twenty-five left brain-damaged patients included fourteen with no degree of apraxia. There were ten control participants. All subjects were right-handed but tested with their left hand (ipsilesional hand for patients). Results showed that, for the patient group the performance of the 'pantomime' condition was significantly worse than the 'demo' and 'use' conditions for both tasks. This indicated that affordance activity occurred due to the availability of the tool in the 'demo' condition and of the tool and recipient object in the 'use' condition. Control participants performed better than patients in all conditions for the hammer task and in both 'pantomime' and 'demo' for the ladle scoop task. However, when patients executed scooping soup with a ladle into a soup plate, their performance score was comparable to the control group.

Similarly to the grounded cognition affordance theory discussed by Mizelle and Wheaton (2010) the authors suggested that an action plan required integration of knowledge of how to use a familiar tool with the goal of the action. They also observed that the more complex task, i.e. the movement of the ladle needing arm rotation, was executed more efficiently than the simpler hammering task. As well as affordances playing a part where the recipient object is available, they believed that for the ladling task the increased working memory workload for the more complex movement was actually beneficial to motor planning and execution.

Summarising this section, there is evidence that objects prime (and thus assist) actions in various patient groups. However, there were no time constraints in any of these studies. Timed decision making by patients, such as the aforementioned congruency study by Goslin et al. (2012), might give greater insight into affordance activity after either left-hemisphere or right-hemisphere brain damage. Indeed the length of time that an object remains available may affect the usefulness of any automatic affordance. Therefore, investigating the temporal nature of affordance could provide evidence relating to the optimum timing for object presentation intended to cue movement (and perhaps promote neuroplasticity) after stroke. Physical reintroduction of objects via breaks in presentation may assist neural plasticity due to newly induced affordances.

1.9 Virtual Reality Interventions

Specifically timed object reintroduction could easily be integrated into virtual reality interventions. Incorporating affordance-related environments in virtual

reality (VR) game programs is already a therapeutic recommendation in cases of childhood cerebral palsy and developmental coordination disorder (Wilson, Green, Caeyenberghs, Steenbergen, & Duckworth, 2016). Research into the use of VR incorporated into stroke rehabilitation is ongoing, with varying degrees of success (Alankus, Lazar, May, & Kelleher, 2010; Burke et al., 2009; Crosbie et al., 2008; Morrow, Docan, Burdea, & Merians, 2006; Saposnik et al., 2010). Some studies included the possibility of game use at home (e.g. Alankus et al., 2010; Standen et al., 2015). Standen et al. (2015) carried out a VR glove home trial with patients who were no longer receiving other forms of upper limb therapy. Data relating to their use of the program along with motor ability and any improvements were sent remotely to clinicians. While some patients found this form of self-regulated activity to be motivating, many found technical issues and competing commitments prevented them from fulfilling the recommended number of days and duration of use. Similarly, Burke et al. (2009) produced several different types of games and, after feedback from a healthy control group, recruited three stroke survivors to trial them. Each participant enjoyed the games, with differing opinions on some aspects, but all found the built-in adaptive difficulty feature increased the pace of the games too quickly. This demonstrates the need for customizable therapeutic games.

So far, comparatively small numbers of stroke participants have undertaken VR therapy trials (see Viñas-Diz & Sobrido-Prieto (2016) for a systematic review). Results evaluating the most useful style of game and success rates for upper limb rehabilitation in stroke survivors are inconclusive. Due to the nature of stroke, the many types of upper limb deficits, (e.g. hypertonia, oedema, pain) and the degree to which these affect an individual, much more research is

needed before VR games are likely to be used widely in stroke rehabilitation. However, the possible influence of affordances has not yet been a factor in the timing of object introduction in these interventions.

Some of the aforementioned studies have already considered the value of affordances to overcome motor deficits but it should be stressed that none of these have evaluated the importance of the length of time that an affordance is active within the brain. This thesis aims to provide further knowledge of the time-course of affordances and contribute to the knowledge of affordance activity in post-stroke participants with a focus on how timing may be relevant in therapeutic interventions.

1.10 Summary and Thesis Outline

In the 40 years since J. J. Gibson first coined the term affordance, discoveries have been made of associated neuronal populations in ventral and dorsal stream processing. Recognition has been given to the timing of affordance activity after presentation of different objects. However, individual studies have been variously limited, for example by the type of objects presented to participants e.g. two dimensional photographs, or by whether they involve passive viewing or require a motor response (with each method having both strengths and weaknesses). Therefore, further determining the onset, duration and offset of naturally occurring affordances is, in itself, a subject worthy of greater research and which this thesis sets out to address. Here, a novel approach of manipulating the position of the dominant hand without varying visual input is investigated, in order to vary the functional implications of an

object, together with stimuli being presented through a stereoscopic viewer to appear as three dimensional. A range of methodologies are used, including behavioural experiments, transcranial magnetic stimulation (TMS) and electroencephalograpy (EEG). Both of the latter neuroscientific techniques, while having considerable spatial limitations, have excellent temporal properties for observing brain activity, and are outlined in Chapter 2.

Chapter 3 presents an EEG affordance experiment with healthy control participants viewing stimuli through a stereoscopic viewer in two different postures. This is extended in Chapter 6, which begins to address the second research question of whether affordance could play a part in stroke rehabilitation. Stroke survivors who had reduced upper limb function were recruited for this EEG experiment, along with age-matched controls, to ascertain whether affordance activity exists after stroke.

Chapter 4 is an investigation using TMS to observe motor evoked potential (MEP) affordance activity in healthy control subjects while they viewed objects through the stereoscopic viewer in the two different postures.

Chapter 5 is a response time experiment relating to differences in viewing two and three dimensional stimuli.

Chapter 7 is a follow-up TMS experiment investigating the influence of repeated stimuli presentations on MEPs obtained from specific muscles.

Finally, a summary of the investigations and their contribution to current knowledge of affordances is presented in Chapter 8.

Chapter 2

Methodology – recording brain activity using TMS and EEG

2.1 Introduction

Many studies suggest the existence of affordances (e.g. Carpaneto et al., 2011; Grèzes et al., 2003; Murata et al., 1997; Nicholson et al., 2017; Raos et al., 2005; Tucker & Ellis, 2001) but these demonstrations sometimes require that we assume a certain amount of naivety on the part of research subjects. If the volunteer has to passively view, for example, carpentry hand tools, then imagining how they would use such tools could bias the experiment result compared to another volunteer who has not engaged in such motor imagery. Animal models may credibly fulfil such naivety criteria but are likely to introduce different issues. Even with shared common features in motor control for reaching and grasping, inter-species differences in kinematics and morphology have been identified between humans and monkeys. Posture of the torso, shoulder, elbow and wrist of the macaque differs to humans (Christel & Billard, 2002), as does thumb pressure and adjustment time for different precision-grips (Viaro et al., 2017). Decision-making paradigms with non-human primates are also limited by the need to train monkeys to perform a response for a reward (Nelissen & Vanduffel, 2011). Equally, whatever object stimuli are offered, the repertoire of tool and object knowledge is hugely greater in humans. For example, humans are experienced in a choice of cutlery; not only are they usually able to identify when to use a knife, fork and dessert spoon, but also a teaspoon, a serving spoon or a carving knife. Tool familiarity plays a part in

generating affordances (Creem-Regehr & Lee, 2005; Vingerhoets, 2008) so constraints in the variety of familiar objects in animal models may restrict results, subsequently reducing their generalisability to inform human studies.

With these considerations in mind, recruitment of human volunteers is essential for the current research questions; to identify the time-course of affordance-related brain activity and to determine any benefit of stimuli producing affordances in stroke rehabilitation. In humans, methods for monitoring brain activity can be divided into two main types. Neuroimaging with good spatial properties includes functional magnetic resonance imaging (fMRI) and positron emission tomography (PET). Other techniques have good temporal properties, particularly transcranial magnetic stimulation (TMS) evoked measures of corticospinal excitability, and electroencephalograpy (EEG). The two former methods have expensive installation and running costs, requiring large-scale equipment, and provide relatively little temporal knowledge. PET also has safety considerations for non-clinical and for repeated scanning due to the introduction into the body of radioactive ligands. TMS and EEG are comparatively inexpensive, requiring a limited amount of equipment and are relatively easy to use so lend themselves well to laboratory research without significant funding. These two methods have successfully monitored affordance-related brain activity, e.g. Buccino et al. (2009) and Makris et al. (2011) for TMS and Goslin et al. (2012) and Proverbio et al. (2011) for EEG. However, as can be seen from these studies, measuring the onset, duration and offset of affordances has produced inconclusive results. To contribute to this knowledge, the research described in this thesis has made use of both TMS and EEG. Each method is briefly explained here, with emphasis on their advantages and limitations.

2.2 TMS

Transcranial magnetic stimulation (TMS) is a non-invasive technique which is widely used in clinical and research settings. As a diagnostic tool, it can aid assessment of cortico-spinal pathways, thereby determining motor neuron deficits in various motor neurone diseases (Miscio, Pisano, Mora, & Mazzini, 1999; Pohl et al., 2001), and be used to observe interhemispheric interactions in motor function recovery from stroke (Murase, Duque, Mazzocchio, & Cohen, 2004; Shimizu et al., 2002). In such investigations electromyographic (EMG) measurements of a motor evoked potential (MEP) are taken from a specified muscle activated by TMS applied over the motor cortex.

2.2.1 Physics and Physiology

An electric current passing through a coil of wire induces a time-varying magnetic field (or magnetic flux density). In a suitable conductor, such as human tissue, the magnetic flux in turn induces an electric field (proportional to the rate of change of the magnetic field) and an Eddy current, perpendicular to the flux and in the opposite direction to the original current. This principle is used in TMS coils. Transcranial magnetic stimulators have a capacitor which is charged to a very high voltage and when discharged produces a current of thousands of amps into the coil. The energy necessary to cause the discharge is around 500 Joules and is transferred from the capacitor to the coil in around 100μs (Jalinous, 1998). This speed of discharge allows the magnetic field to rise rapidly and then decay more slowly, around 1ms (Figure 2.1).

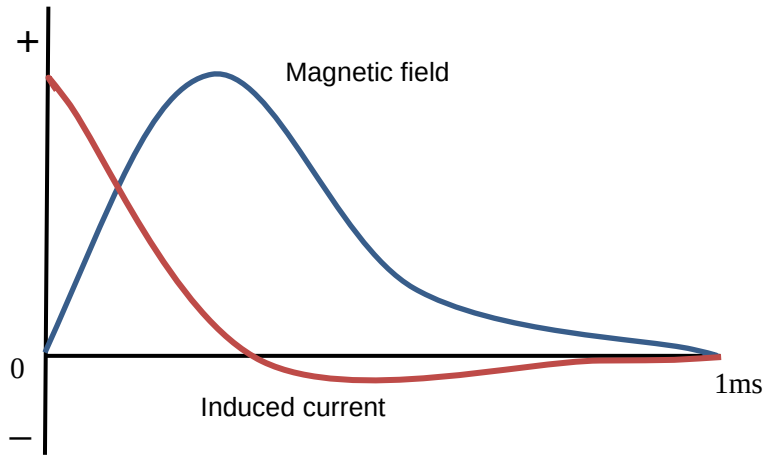


Figure 2.1. Diagram showing resulting magnetic field and the current induced from a typically critically damped circuit produced by a transcranial magnetic stimulator. (Adapted from figure 1.3 in Chapter Electromagnetism of Oxford Handbook of Transcranial Stimulation by Epstein (2008) and from figure 7.1 (B) in Introduction to Basic Mechanisms of Transcranial Magnetic Stimulation by Austin and Rothwell (2017)).

The time-course of the pulse depends on the capacitance (C) of the capacitor, inductance of the coil (L) and the resistance in the circuit (R). It also depends on a damping factor (D) where

$$D = R\sqrt{C/2}\ \sqrt{L}$$

If D<1 the circuit is underdamped and the induced current will oscillate, if D>1 the circuit is overdamped and the current will rise slowly. If D=1 the circuit is critically damped and the current rises rapidly to a peak and dissipates without oscillating (Mills, 1999). (Figure 2.1).

Biphasic stimulators have a return current which is suited to bilateral stimulation. Monophasic stimulators, such as the one used in the following experiments (Figure 2.2), also contain a thyristor, effectively allowing current to flow in just one direction and making a short, directional pulse.

Figure 2.2. Monophasic stimulator and ‘figure of eight’ coil.

The original TMS circular coil produces the magnetic field through the centre of the coil. However, a ‘figure of eight’ style coil (Figure 2.2), having current flowing in opposing directions (clockwise and anti-clockwise) in each coil from posterior to anterior, produces a focal point between the two windings. Secondary, vastly smaller fields occur under the centre of each coil. The monophasic aspect means that direction of current induced in human tissue relies on the positioning of the coil as the current flow in the coil does not get reversed. Maccabee, Amassian, Erberle, & Cracco, (1993) extensively tested amphibian and mammalian peripheral nerves in vitro. They observed that the greatest excitation occurred in the nerve relating to the anterior point where double coil windings separated. Not, where might be expected, centrally between the windings. In the human brain, TMS causes a current of between 1 and 20mA/cm^2 (Jalinous, 1998) and the resting potential of cell membranes is around -70mV. Nerve cell bodies, axons and dendrites are hyperpolarized (the cell membrane becomes more negative) where current enters and depolarized (the membrane becomes less negative) at points where current leaves. If depolarization exceeds a threshold level, dependent on intensity and duration of induced current, then an action potential is triggered. However, intensity must

be at or above the rheobase value, otherwise excitation does not occur, whatever the duration. Thresholds differ for different neural components with axons having lower thresholds than cell bodies. For long fibres, excitation occurs at bends. Cortical neurons are much smaller than the coil size, so are exposed to a fairly uniform electric field. Here, excitation occurs at bends or changes in diameter, for example from the cell body to the axon (Mills, 1999).

2.2.2 Different Forms of TMS

There are three main types of stimulation; single pulse, paired pulse and repetitive TMS. Single and paired pulses are generally considered safe and non-invasive. However, as currents are being induced in brain tissue, as a precaution against any risk of seizure or syncope, participants for non-clinical research are screened for exclusion criteria such as metal implants, history of head injury or seizures, certain medication or any diagnosis of epilepsy in immediate family members. It is also standard procedure to stimulate only at certain percentages of the individuals' resting motor threshold (RMT). The actual percentage varies between research groups, some choosing only to stimulate up to 120% RMT (e.g. Buccino et al., 2009; Franca et al., 2012; Makris et al., 2013) although some groups stimulate as high as 150% RMT (e.g. Khedr, Ahmed, Ali, Badry, & Rothwell, 2015; Schambra, Sawaki, & Cohen, 2003). Possible transient side effects from single pulse TMS are headache, local pain, neck pain, toothache, paresthesia or hearing changes (Rossi et al., 2009). During the experiments reported in later Chapters, to prevent such adverse effects, the position of the coil was continuously monitored and the intensity and number of pulses given was no greater than necessary to satisfy the research question. Throughout each session, the participant was also

encouraged to inform the researcher of any discomfort so that this could be rectified by making a minor adjustment to the coil position or to the stimulus intensity.

As a form of therapy, repetitive TMS (rTMS) is being investigated in situations such as to aid recovery from stroke (Hummel et al., 2008). Its use may be to inhibit cortical activity contralateral to the site of infarct or to directly increase activity in the affected hemisphere (Dafotakis et al., 2008; Ziemann, 2005). It is also used as an aid to improve outcomes in differing psychiatric conditions such as major depression and food cravings (Lisanby, Kinnunen, & Crupain, 2002; Uher et al., 2005), and is being considered as possibly instrumental in slowing the rate of neurodegenerative diseases such as amyotrophic lateral sclerosis (Di Lazzaro et al., 2004, 2010). There is continuing investigation of rTMS, particularly as a psychiatric tool and in the manner of cognitive lesioning. Disruption of perception, or a virtual lesion, can occur if stimulation is applied whilst the subject is performing a cognitive task. Conversely, depending on stimulation intensity and the excitable state of neuronal populations rTMS can also have facilitatory effects (Silvanto & Cattaneo, 2017).

2.2.3 TMS over the Motor Cortex

Of interest for this research is that stimulation can result in the innervation of hand muscles; for example, the first dorsal interosseous (FDI), which is usually activated in a forefinger and thumb precision grip, and abductor digiti minimi (ADM), activated by a whole hand power grip. The induced current flow from a

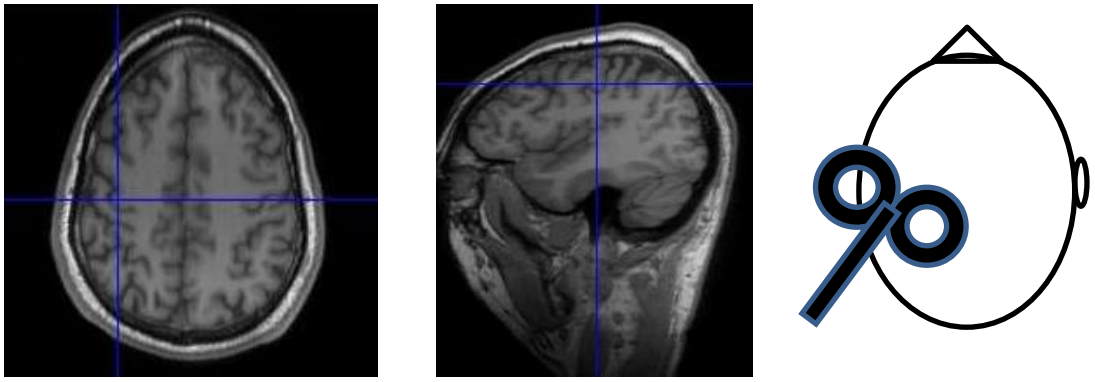
TMS pulse is parallel to the surface of the brain and excites transsynaptic pyramidal neurons. The pulse can be distorted by the sulci, gyri and the anisotropic character of the brain (Opitz, Windhoff, Heidemann, Turner, & Thielscher, 2011; Thielscher, Opitz, & Windhoff, 2011). However, an appropriate stimulus intensity delivered at a suitable site over the motor cortex can produce sufficient excitatory synaptic inputs to produce a descending volley of indirect-waves (I-waves) through corticospinal neurons (Austin & Rothwell, 2017). These can innervate muscles in the hand producing a measurable MEP which can be recorded by EMG. A full explanation of I-waves and associated D-waves can be found in, for example, (Mills, 1999; Rothwell, Thompson, Day, Boyd, & Marsden, 1991).

(a) (b) (c) (d)

Figure 2.3. Adapted from Caulo et al.(2007). In the axial plane; shapes depicting the 'handknob' within the motor cortex. (a) 'omega', (b) 'epsilon', (c) medially asymmetric epsilon and (d) laterally asymmetric epsilon.

The specific part of the motor cortex correlating with activity in the hand muscles has been named 'the handknob' (Yousry et al., 1997). It has been identified on the pre-central gyrus as an omega shape or variations of an epsilon (Caulo et al., 2007) on the axial plane (Figure 2.3) and as a hook in the sagittal plane. The omega shape and the hook can be easily identified at the

sight of the crosshairs on the structural MRI scans in Figure 2.4 (a) and (b) respectively.



(a) (b) (c)

Figure 2.4. Scans reproduced by kind permission of Dr. Mark Bowden. (a) MRI scan with crosshairs showing the 'handknob' as an omega shape in the axial plane; (b) MRI scan with crosshairs showing the hook in the sagittal plane; (c) diagram showing 'figure of eight' coil over motor cortex.

The maximum magnetic field produced by a 'figure of eight' coil occurs under the anterior section where the two windings separate so this is borne in mind when positioning over the scalp to stimulate hand muscles (Figure 2.4 (c)). As well as position on the head, the angle of the coil in three-dimensional space must also be considered. Correct positioning of TMS delivered over the motor cortex to contralateral hand muscles has revealed that corticospinal fibres conduct rapidly to spinal motor neurons, resulting in EMG recordings within 25ms (Austin & Rothwell, 2017). Usually, TMS output intensity is a percentage of the participant's resting motor threshold. Sizes of motor evoked potentials (MEPs) differ not only due to the intensity of the pulse but also as participants prepare to activate a particular muscle, therefore providing a corticospinal measure of a plan for action. During a behavioural task MEPs may be assessed

at any time-point and represent activation within a relatively spatially constrained source; the corticospinal tract.

Here, the objectives of the TMS investigations into timings of affordances were to obtain the most effective results in the FDI and ADM with the least discomfort to volunteers. Therefore stimulation was carried out with a monophasic stimulator delivering single pulses using the very focal ‘figure of eight’ coil positioned over the motor cortex in a posterior to anterior direction.

Further details of the design of the experiments and use of equipment are contained in the relevant Methods sections in the two TMS chapters, namely, Chapter 4 and Chapter 7.

2.3 EEG

2.3.1 Introduction to Electroencephalography

EEG has similarities with TMS in terms of its ability to determine the timing of brain activity in response to external stimuli. TMS induces an electric current creating neuronal activity, even to the extent of generating volleys of I-waves through the corticospinal tract. In contrast, EEG records changes in cortical neuronal activity from all regions of the brain by identifying subtle changes of voltages across the scalp and so is completely non-invasive. Although having spatial limitations, the temporal qualities of EEG are excellent, having millisecond precision (Sanei & Chambers, 2007). To reduce the recording of unwanted artefacts, especially from lights and portable appliances connected to

the 50Hz mains supply, the experimental procedure is often conducted in an electronically shielded room.

There are variations of the types of equipment available but they are likely to consist of the following hardware and software:

- an array of electrodes attached to a well-fitting cap, usually with conducting gel to reduce scalp-electrode impedance
- amplifiers to improve signal to noise ratio
- USB adaptor to connect amplifiers to the recording computer
- an analogue-to-digital converter to digitize the amplified voltage potential differences
- high and low band pass filters to remove artefacts generated below and above certain frequencies
- specific artefact rejection software to further eliminate unwanted externally and internally produced artefacts, e.g. from eye blinks.

Electrode arrays commonly comprise 64, 128 or even 256 channels placed on the cap. They are positioned in the International 10-20 system (Jasper, 1958) (Figure 2.5), modified for larger arrays, into the10-10 system and 10-5 system respectively (Jurcak, Tsuzuki, & Dan, 2007; Seeck et al., 2017). The channels are usually given identifiable letters and numbers. By convention, negative numbers indicate the left hemisphere and positive numbers indicate the right hemisphere with z representing centrally aligned electrodes from nasion to inion. In Figure 2.5 main positions F, C, P, T and O indicate frontal, central, parietal, temporal and occipital respectively with further, intermediate, divisions being AF, FC, CP and PO. Greater numbers of electrodes produce a better

result for signal source location (Lopes da Silva, 1990) whereas, in the growing area of brain-computer interfaces, very few electrodes are required (Sanei & Chambers, 2007).

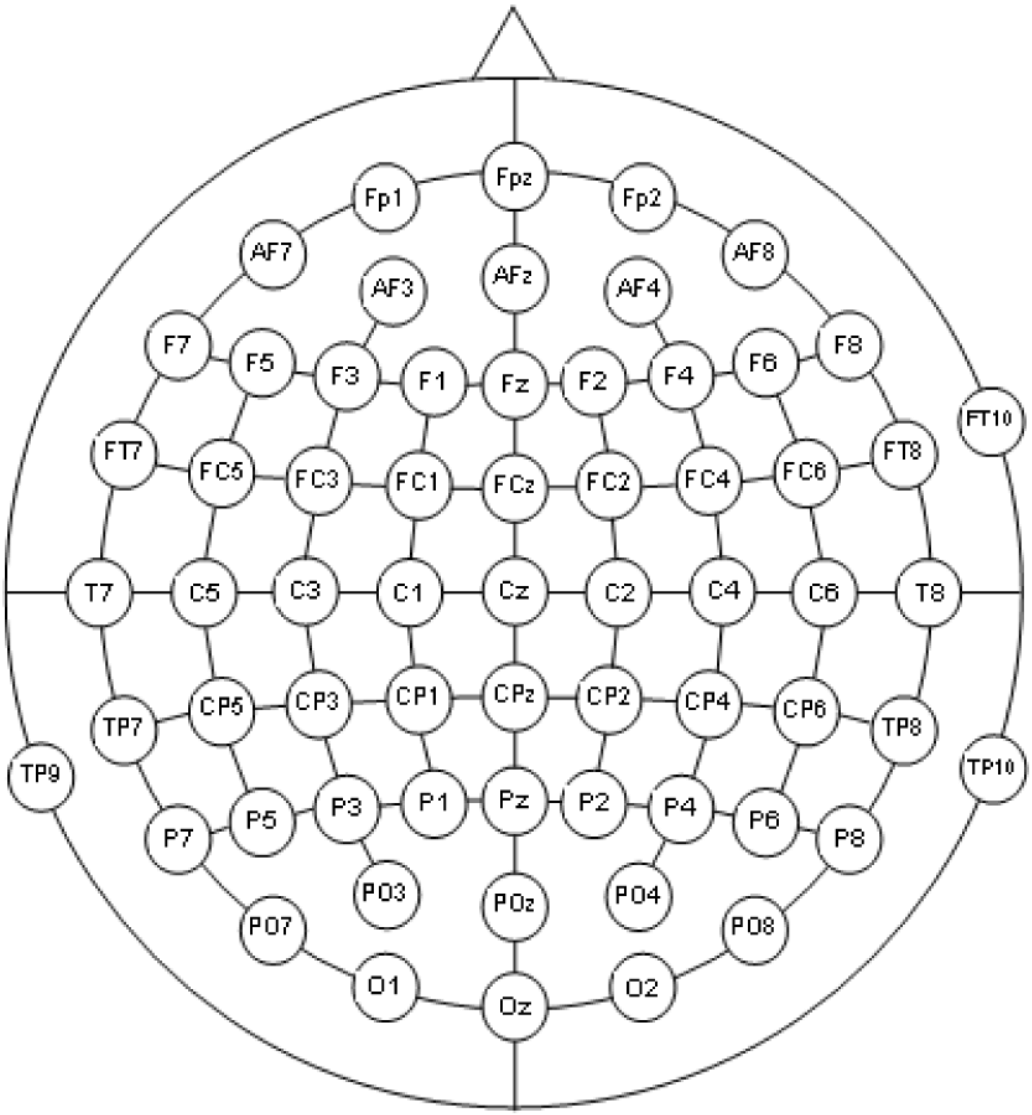


Figure 2.5. Example of the International 10-20 system, in this case with 64 electrodes.

For researchers, this equipment is easy to use and requires minimal training. For participants there may be slight inconvenience with the hair needing to be washed due to the use of conducting gel under electrodes, but otherwise discomfort is negligible and there should be no adverse effects. The only safety issue is during investigations with epileptic patients that include hyperventilation

or photic stimulation, either of which are able to induce a seizure. However, The British Society for Clinical Neurophysiology produces safety guidelines for researchers, as does the International League Against Epilepsy (Kasteleijn-Nolst Trenité et al., 2012).

2.3.2 Neural Basis of EEG

Similarly to other cells in the body, neurons are associated with specific chemical ions. Potassium (K^+) and chloride (Cl^-) are in high concentrations in the intracellular space with sodium (Na^+) and calcium (Ca^{++}) ions in high concentrations in the extracellular space. The greatest neuronal activity is caused by action potentials with the movement of Na^+ and K^+ ions. The resting potential of the neuron membrane is around -70mV, and although many stimuli from synapses reach the axon hillock it is not until one causes the neurone to reach a threshold of -55mV that an action potential will be triggered. When this threshold is reached, voltage-gated Na^+ ion channels are opened allowing Na^+ to rush in making the membrane potential more positive which, in turn, causes more Na^+ ion channels to open and more Na^+ to rush in. This depolarization continues until the Na^+ ion equilibrium is reached at a positive voltage. According to different literature this may be around +30mV (Sanei & Chambers, 2007), +52mV (Hämäläinen, Ilmoniemi, Knuutila, & Lounasmaa, 1993) or +62mV (McCormick, 2004). At this point voltage gated K^+ ion channels have enough voltage to make them open. There is now such a positive charge on the inside of the cell that, positive repelling positive, K^+ ions leave the cell causing hyperpolarization until K^+ ions reach equilibrium at around -89mV to -103mV (Hamalainen et al., 1993; McCormick, 2004; Sanei & Chambers, 2007). At this

stage three Na^+ ions leave the cell and two K^+ ions enter sufficiently often (via the Na-K pump) to return the membrane to its resting state.

It is not the action potential itself that is most detectable by EEG. An action potential triggers the release of neurotransmitters at the axon terminal. The transmitter molecules travel across the postsynaptic cleft to receptors on the postsynaptic cell. In turn, receptors change shape, activating ion channels on the cell membrane and causing an electric current along the interior of the postsynaptic cell. If the receptors allow Na^+ ion channels to be opened then Na^+ flows into the cell and it depolarizes, so that there is an excitatory postsynaptic potential (EPSP). As this occurs, current also flows into the cell (current sink). Conversely, if channels are opened to allow K^+ ions to flow out of the cell then this is also the direction of the current (current source) and the cell becomes hyperpolarized, creating an inhibitory postsynaptic potential (IPSP). Postsynaptic potentials are the most significant components of EEG signals; although having smaller amplitude than action potentials, they have a far longer duration of tens of milliseconds compared to ≤2ms (Bucci & Galderisi, 2011; Lopes da Silva, 2010).

As there is no accumulation of charge, this means that synaptic current flowing through a sink or a source is compensated by current flowing in the opposite direction elsewhere on the neuron creating a current dipole. For an EPSP where there is a synaptic sink, there are passive sources along the soma-dendritic membrane. Similarly for an IPSP synaptic source, there are passive sinks along the soma-dendritic membrane (Lopes da Silva, 2010). Pyramidal neurons are generally aligned perpendicular to the skull, with branching apical

dendrites closest to the surface, which is where most EPSPs occur. Although some individual neurons may be aligned so that the direction of their dipoles cancel each other out, when populations of pyramidal neurons are receiving post-synaptic potentials they tend to synchronise, effectively acting as an equivalent current dipole (ECD). Electric fields are generated around ECDs, as are voltage potentials which are detectable on the scalp by EEG and provide the signals that generate waveforms (Hämäläinen et al., 1993; Lopes da Silva, 2010; Song et al., 2015).

2.3.3 Components of the EEG Signal

The first human EEG recording was by Hans Berger in 1924 at the University of Jena. In 1929 he reported his work of five years earlier when he recorded the first human alpha (α) wave at around 10Hz. The α-wave is now generally recognized at 8 - 13Hz. Other identifiable waveforms have been named as beta (β) at 13 - 30Hz (Pogarell, 2011), delta (δ) < 4Hz, theta (θ) at 4 – 8 Hz and gamma (γ) > 30Hz. (Some authors report smaller ranges for β frequencies). This oscillatory activity is generated by cortical and subcortical neurons and has the effect of altering the voltage potentials across the scalp.

More important for this research is the existence of event related potentials (ERPs). After presentation of a stimulus, firstly, does an affordance occur and, if so, when is its onset and how long is its duration? The EEG experiments were designed primarily for ERP investigation while participants passively viewed stimuli. The recording process is only outlined here as further details are reported in the EEG experimental chapters.

ERPs are recognizable changes in scalp voltage potentials, milliseconds after the presentation of a stimulus (the event). Similarly to the studies in this thesis, it is likely that most researchers are comparing stimuli in different experimental conditions. This means that there needs to be a suitably large number of stimuli per condition and a similar amount of stimuli across conditions. For every participant the EEG signal has to be segmented into a time-window around the stimulus. Time-windows are summated for all stimuli in that condition and averaged. This is performed for each condition. ERPs for a single participant may then be observed in the waveform at individual electrode sites or averaged across a group of electrodes. For a clearer picture, all participants' ERPs need to be averaged together. Again carried out separately for each condition, this can provide a grand averaged waveform where one or more positive- or negative-going peaks are observed. The numerical peak voltage, the time it occurred and a calculation of the area under the curve of the peak may all be extracted for each participant, allowing statistical analysis comparing conditions to be performed on these figures. Measuring individual ERP components in different conditions does, unfortunately, create the potential for a large number of dependent variables and thus an inflation of Type I errors. However, this can be somewhat mitigated by focussing on a few components, ideally identified a priori.

2.3.4 Source Localization

Another feature of EEG recordings is source localization. While other neuroimaging methods, such as fMRI, are far superior for determining the source of brain activity, it is possible with EEG to locate probable positions that

generate the scalp potentials. In the second EEG experiment reported here, two groups of participants were recruited; people who had lesions caused by stroke and neurologically healthy age-matched control volunteers. It was useful to investigate source localization in the control group to consider what brain regions might be active in producing affordance-related ERPs, especially if similar ERPs occurred in the stroke survivor group. This estimation was carried out using the BrainVision Low Resolution Brain Electromagnetic Tomography (LORETA) software. Here I provide a brief overview of LORETA but for a full explanation, please see, for example Pascual-Marqui, 1999; Pascual-Marqui, Michel, & Lehmann, 1994; Phillips, Rugg, & Friston, 2002.

To obtain information about the source of scalp potentials (the 'inverse problem') initially a 'forward problem' has to be solved. The forward problem can be described as finding the voltage on the scalp (**V**) which is produced by a current dipole (**J**). The dipole is affected by the shape, volume and conductivity of the media through which it flows (**K**) (Gramfort, Papadopoulo, Olivi, & Clerc, 2011; Pascual-Marqui, 1999). A current dipole is characterized by 6 parameters; 3 for location (x, y, z) and 3 vectoral components, being magnitude and 2 orientations (θ and φ in spherical co-ordinates) (Figure 2.6).

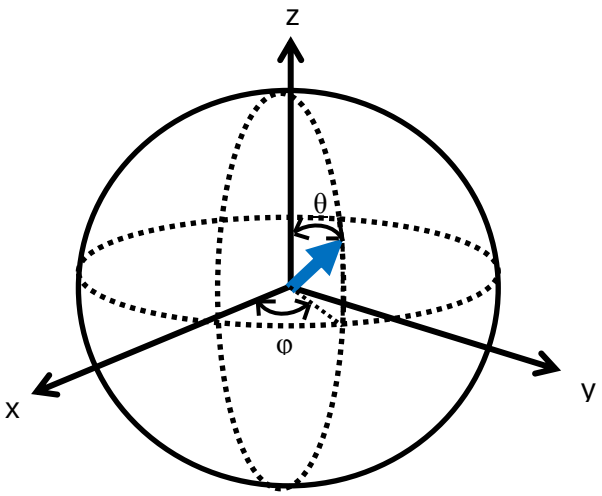


Figure 2.6. Modelling a dipole in Cartesian co-ordinates. (Adapted from Kidist, Naranjo, & Hoppstädter, (2017) BrainVision Analyzer 2 Webinar).

A matrix $\vec{\mathbf{J}}$ represents the current source for a single dipole but, as mentioned earlier, primary current sources arise from synchronized pyramidal cells (ECDs). The cortex can be divided into discrete patches represented by matrix $\mathbf{J}$ for **M** number of sources.

$$\vec{\mathbf{J}}_{(3x1)} = \begin{bmatrix} J_x \\ J_y \\ J_z \end{bmatrix} \text{ for single source} \qquad \mathbf{J}_{(3Mx1)} = \begin{bmatrix} \vec{J}_1 \\ \vec{J}_2 \\ \vdots \\ \vec{J}_M \end{bmatrix} \text{ for M sources}$$

The relationship between voltage and current density is assumed linear and therefore may be defined by:

$$\mathbf{V}_{(Nx1)} = \mathbf{K}_{(Nx3M)} \cdot \mathbf{J}_{(3Mx1)}$$

Where **V** is an *N* ▪ 1 matrix comprised of all *N* scalp potential differences, J is the current source density matrix and **K** is the lead field matrix (Gramfort et al., 2011) relating head model, volume and conductivity by Poisson's Equation

$$\nabla \cdot (\sigma \nabla V) = \nabla \cdot J$$

(∇ = derivative operator, σ = conductivity, V = electric potential, J = current source density) (Gramfort et al., 2011)

As brain shape, size and volume vary across individuals, unless structural MRI scans are available for each participant, it is necessary to use a standard template, such as the Montreal Neurological Institute (MNI) 305 template. This is an average of MRI scans of 305 individuals. For conductivity, a spherical, concentric 3- shell head volume model of the brain, skull and scalp can be implemented and then both co-registered to the Talairach Atlas (Talairach & Tournoux, 1988).

In summary, the solution to the forward problem determines the electric potentials on the scalp created by the primary current sources (Figure 2.7).

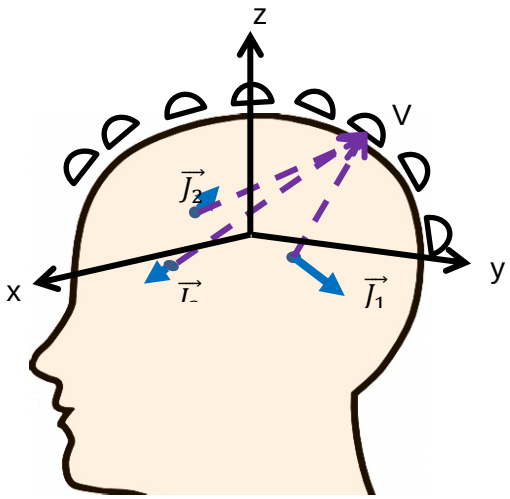


Figure 2.7. Schematic of the forward solution. (Adapted from Kidist et al. (2017) BrainVision Analyzer 2 Webinar).

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The inverse problem is to find the position, orientation and magnitude of the current dipole, or ECD, from the voltage measurements obtained by the forward problem. In matrix form:

$$\hat{J}_{(3Mx1)} = T_{(3MxN)} \cdot V_{(Nx1)}$$

Where the current source $\hat{\mathbf{J}}$ is obtained from the voltage measurements **V** that formed the solution to the forward problem, acted upon by the generalized inverse matrix **T**.

To solve the inverse problem requires certain assumptions; in LORETA:

a priori location of the source space,

estimation of the distribution of the current density across the source space. (Pascual-Marqui et al., 1994)

The LORETA source space is confined to grey matter in the cortex and hippocampus (defined by the Talairach Atlas (Talairach & Tournoux, 1988)) and contains a three dimensional grid of 2394 voxels, each of $7mm^3$. The aim is to estimate the dipole magnitude at each voxel. Basically, matrix **T** is the inverse of matrix **K** in the forward problem. Again, use is made of the concentric 3-shell head volume model and MNI 305 template, this time also co-registering the electrode positions (Figure 2.8). Matrix **T** involves the Laplacian operator for the second derivative of the scalar field, i.e. the derivative of the gradient of the electric field relating to a scalp potential. LORETA also assumes that, due to synchronicity, neighbouring sources have similar orientation and magnitude (Pascual-Marqui et al., 1994), which allows a weighting factor to be included in **T**. Solving the inverse problem, the estimated source should be equal to the source identified in the forward problem: $\hat{\mathbf{J}} \approx \mathbf{J}$.

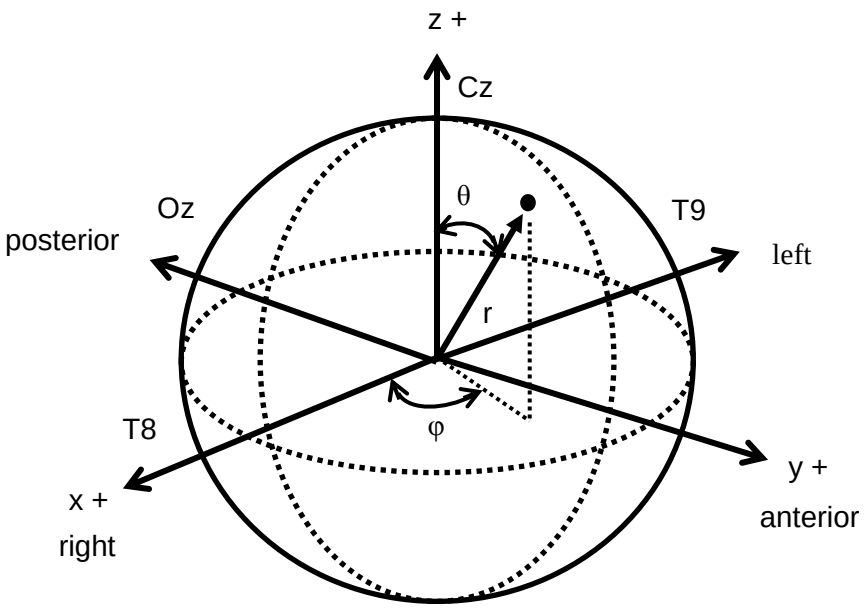


Figure 2.8. Diagram showing co-registration of the head model, Talairach atlas and four electrode positions. A point on the scalp is represented in spherical coordinates, with r = 1. (Adapted from BrainVision Analyzer 2 Webinar).

For more details regarding this method and other, possibly more effective, methods to locate the sources of brain activity relating to scalp potentials (e.g. independent component analysis, FOCUSS algorithm and MUSIC algorithm), please see, for example Pascual-Marqui et al. (1994); Pascual-Marqui (1999); Phillips et al. (2002); Sanei and Chambers (2007).

Although LORETA requires assumptions regarding conductivity, source space location and the distribution of current density, it was a suitable tool for the purposes of this research. For the experiment reported in Chapter 6 the objective was simply to identify active sites within an ERP time-window and to compare the magnitude of current density, at those sites, across conditions.

2.4 Summary

TMS and EEG methodology are reported here as each technique has value when measuring the timing of neural activity. Particularly valid for this research was the ability to record neural responses to stimuli when there was no verbal or physical response required from the participant. EEG was used primarily to observe ERPs after a variety of stimuli were presented in different conditions. In the second EEG experiment, as well as obtaining ERP information, source localization was included to detect any differences in ventral and dorsal stream activity when the different types of stimuli were viewed. In the first experiment utilizing TMS, pulses were given at different times while participants viewed two types of stimuli. This was to allow investigation of the timing of possible affordances from the amplitude of the MEPs elicited from the ADM and FDI muscles. The second TMS experiment attempted to identify whether passive

viewing of objects had an effect on the MEPs later elicited from each muscle, perhaps via cortical plasticity as evidenced during studies of motor learning. Full details of methods are given in the relevant study chapters.

The next chapter reports the first EEG experiment. Recordings were taken from neurologically healthy, young participants while they viewed stimuli through a stereoscopic viewer and sat with either their right or left hand close to the screen. ERPs were identified for object stimuli which had been categorized depending on their affordance-like properties.

Chapter 3

EEG study to detect affordance activity in healthy participants

Adapted from “Objects rapidly prime the motor system when located near the dominant hand” published in Brain and Cognition volume 113 (2017) pages 102 – 108 and co-authored with Corinna Haenschel, Maciej Kosiło and Kielan Yarrow.

3.1 Introduction

The term affordance was first introduced by JJ Gibson in 1977 who suggested that just by viewing an object we perceive how to use it. In recent years it has often been used to describe the idea that even when there is no intention to act, the intrinsic properties of an object will potentiate motor planning. This has prompted many studies investigating the existence of affordances (i.e. automatic priming of the motor system by viewed objects) in both human and non-human primates (Grèzes et al., 2003; Murata et al., 1997; Rice, Valyear, Goodale, Milner, & Culham, 2007; Tucker & Ellis, 1998; Tucker & Ellis, 2001; Valyear et al., 2007).

For example, Murata et al. (1997) took recordings from individual neurons in the ventral pre-motor area F5 of a macaque monkey. The animal was trained to observe physical objects and, on some trials only, was expected to pick up the object. 49 neurons were found to be task-related. 25 of these were described as motor neurons and the other 24 as visuomotor neurons. All 49 discharged when the monkey picked up an object. Interestingly, though, the 24 visuomotor neurons also discharged when the animal viewed objects whether or not it was a 'pick-up' trial. Some of these individual neurons also showed selectivity for a small set of similar objects by discharging at a higher rate when these objects were viewed. It was concluded that the visuomotor neurons were responding to the visual features of each object, reaffirming the theory that intrinsic visual properties potentiate motor planning.

Corresponding work with humans has led to much discussion as to which brain regions are similarly activated during passive object viewing. Many human studies that require a motor response focus on conflict in motor planning (e.g. Grèzes et al., 2003; Tucker & Ellis, 1998; Tucker & Ellis, 2001; Valyear et al., 2007). This has sometimes been combined with neuroimaging. For instance, in a functional magnetic resonance imaging (fMRI) congruency task, Grèzes et al. (2003) required participants to make a forefinger and thumb precision grip when viewing any natural object and a whole-hand power grip when viewing any manmade object. Visual stimuli could be either congruent or incongruent for the required type of response. For example, a grape (natural, hence instructing a precision grip response) would be in line with a congruent response, because the response matched the motor priming properties of the object, while a cucumber would be incongruent in this respect. Equally, for manmade objects (instructing a power grip response), a hammer was congruent while a screw was incongruent. Grèzes' group found that reaction times were greater for incongruent trials, presumably due to conflict between the action afforded by the object and the response required for the task. Correspondingly, fMRI activity in various brain regions also differed between the congruent and incongruent trials with most activation occurring in the left hemisphere. Areas correlating with the behavioural results were, in particular, the premotor cortex and also the inferior frontal sulcus, superior temporal sulcus, anterior parietal cortex and superior parietal lobe.

Interestingly, significant fMRI activity has also been observed in the right hemisphere of healthy right-handed volunteers in another type of response task (Rice et al., 2007). Here, graspable or non-graspable objects were shown

orientated to either the left or to the right. After a brief mask stimulus the object was shown again, on some trials with the same orientation and on others with the opposite orientation. Subjects had to respond by pressing one button for same and another for different orientations. In this study fMRI activity was contrasted between repeated and flipped stimuli (using a form of fMRI adaptation) and revealed that the right lateral occipital-parietal junction was selective for orientation but only for graspable objects.

These and many similar findings (e.g. Goslin et al., 2012; Righi et al., 2014; Tucker and Ellis, 1998, 2001) suggest that affordances exist in humans. However, although spatially informative, the temporal resolution of fMRI is less impressive due to the signal delay of the blood oxygen level-dependent (BOLD) response. Hence the exact timing of neuronal activity caused by affordance cannot be deduced from fMRI. Recently there have been several transcranial magnetic stimulation (TMS) experiments (Buccino et al., 2009; Cardellicchio, Sinigaglia, & Costantini, 2011; Makris et al., 2011, 2013) which have contributed to a better understanding of the temporal evolution of affordances. For example, Buccino et al. (2009) stimulated left motor cortex, and showed greater motor evoked potentials (MEPs) 200ms after the onset of objects with handles orientated towards the right than the left and, particularly, that these MEPs were larger for whole handles rather than damaged ones. Makris et al. (2011, 2013) presented objects affording either a precision or power grip, and found modulation in MEPs from the congruent hand muscle groups (consistent with the presence of an affordance) that began 150-300ms after stimulus onset and died away at around 600ms after stimulus onset.

Some recent electroencephalographic (EEG) studies have also sought to measure the timing of affordances by comparing responses to pictures of tools with non-tools (Proverbio, 2012; Proverbio et al., 2011). Proverbio et al. (2011) found significantly greater anterior left hemispheric negativity for the N2 component of the event-related potential (ERP) while viewing tools compared to non-tools. The N2 is the second negative component after stimulus onset and has been associated with motor facilitation (Allami et al., 2014). Using 128 electrodes, Proverbio et al. (2011) computed the N2 from electrode sites AF3, AF4, AFP3h and AFP4h. Their time window was from 210ms to 270ms after stimulus onset. A standardized weighted low-resolution electromagnetic tomography (swLORETA) inverse solution was computed to understand the source of this increased activity for tools. In response to tools it revealed more left than right hemispheric pre-motor activity (Brodmann Area 6), as well as unilateral (left hemisphere) activation of the somatosensory cortex (Brodmann Area 3). The swLORETA computation showed that these areas were not involved in response to other (non-tool) objects. Two other ERP components were also investigated. These were firstly the positive component with peaks usually between 300ms and 600ms after stimulus onset (P300) and secondly a later slow positive component generally appearing between 400ms and 750ms after stimulus onset (late positivity). A greater centroparietal P300 component for tools compared to non-tools was observed between 550ms and 600ms after stimulus onset, whilst a larger late positivity amplitude for non-tools (from anterior frontal and prefrontal electrodes) occurred between 750ms and 850ms after stimulus onset. These have been related to attention for a target stimulus amongst a set of non-targets (Frodl-Bauch, Bottlender, & Hegerl, 1999; Mugler

et al., 2008; Nijboer et al., 2008) and controlled allocation of attention (Schienle, Köchel, & Leutgeb, 2011; Schupp et al., 2000) respectively.

The defining feature of an affordance is that it represents priming of the *motor* system (regardless of the ultimate requirement to act or not). The current experiment was planned to attempt to confirm the existence in the EEG of a differential motoric response to objects that prime grip actions compared to scenes without such objects. In their studies, Proverbio et al. (2011) had two stimulus categories and used pictures of objects that afforded both manual and non-manual actions (e.g. a bicycle and stairs were included in the tool category). Instead, here object stimuli were confined to those relating to the hand and utilised images containing stereo depth cues, which are known to support accurate goal-directed visually guided reach-to-grasp actions (Melmoth, Finlay, Morgan, & Grant, 2009; Melmoth, Storoni, Todd, Finlay, & Grant, 2007; Melmoth & Grant, 2006). A further question arises as to whether the EEG components identified by Proverbio et al. (2011) provide markers of purely motoric brain activation. In a design that simply correlates brain activity with different categories of visual stimuli it is difficult to rule out a purely visual contribution to observed differences. Hence an attempt was made to overcome the problems raised by a reliance on comparisons between visual stimuli in two ways.

Firstly, in addition to the components identified by Proverbio et al. (2011), purely visual discrimination as associated with the posterior N1 ERP component was investigated (Hopf, Vogel, Woodman, Heinze, & Luck, 2002; Mangun & Hillyard, 1991; Thorpe, Fize, & Marlot, 1996; Vogel & Luck, 2000). This component was

used to search for any differences in the visual brain response evoked by the stimuli, in the hope that such effects could be ruled out.

Secondly, because any contrast between object and non-object stimulus categories may introduce systematic visual differences above and beyond those that were intended, an additional manipulation was sought that should modulate the creation of an affordance within the motor system. To this end, participants adopted one of two postures. The first, a sitting posture with the dominant hand close to 3D objects, should promote the generation of an affordance, whereas the second, with body rotated to have the dominant hand far away from the screen, should lessen any affordance (at least within the dominant left hemisphere).

In summary, the question is whether viewing objects in 3D and manipulating the position of the dominant hand can provide compelling evidence of brain activity associated with affordances. A design was introduced in which any effects on ERPs from purely visual differences between objects could be ruled out. The innovation is to provide identical visual stimulation in two posture conditions that vary the functional meaning of objects. Interactions were then identified between posture and image category in the EEG, thereby revealing ERP components that index a fundamentally motoric priming effect.

3.2 Materials and Methods

3.2.1 Participants

29 participants were recruited to passively view 3D photographs of objects and of an empty desk (9 males, 20 females; mean age 28.1 years, SD 5.53 years). All had normal or corrected-to-normal vision with no history of neurological illness. All were right-handed as verified by the Edinburgh Handedness Inventory, adapted from Oldfield (1971). The study was approved by City University Ethics Committee and participants gave written consent.

3.2.2 Stimuli

Initially, 3D photographs were taken of 40 objects positioned on a desk in such a way that no left or right laterality could be ascertained, i.e. either photographs of objects without handles or photographs of objects with the handle positioned centrally. Viewpoint and light source remained constant across photos. To establish object categories for the experiment, 20 independent assessors rated the photos on whether they would use a forefinger and thumb precision grip or whole hand power grip to hold the objects. The assessors used three categories; “always use this type of grip”, “mostly use this type of grip”, or “just more likely to use this type of grip”. A separate independent group of 10 people then rated the objects from 0 to 2 on how familiar they were, with 2 being a very familiar object. A subset of pictures was then chosen which contained good exemplars of objects affording either a precision or power grip (i.e. consistently rated “always” for the relevant grip and predominantly rated 2 on the familiarity scale). For the subsequent experiment, these stimuli were used to construct

three stimulus categories. The first category contained only a single stimulus (an empty desk) while the other two showed objects located on the desk. Object categories consisted of one picture of each of five objects, which would normally be held in either a precision grip (tweezers, drawing pin, button, wedding ring, and paperclip) or a power grip (hairbrush, glass, mug without handle, liquid soap container and knife).

3.2.3 Design and Procedure

Participants were seated in an electrically shielded room, in front of a mounted stereoscope, approximately 45cm from a gamma-corrected CRT monitor refreshing at 109 Hz. Left-eye and right-eye images were displayed side by side, but presented only to their respective eyes via the mirror stereoscope (Stereo Aids, Australia). Initially, participants were allowed time to adjust the viewer so that they observed a single object in three dimensions. For this calibration, two objects, a ball and a sponge, were presented in alternation. These two objects became targets for a subsequent vigilance task.

For the main experiment, on each trial, two fixation dots were shown on screen for 1000ms (to maintain stereo fusion in the interval between pictures) followed by a colour photograph, also for 1000ms (see Figure 3.1A). The task was to passively view the pictures through a stereoscopic viewer, except that participants had to report the two target items (ball and sponge) whenever they appeared (with these trials excluded from the subsequent data analysis). In each block, there were 150 trials with photographs of the empty desk (‘no object’ category) and 150 trials each from the two object categories (precision-

grip objects and power-grip objects) so that each individual object was viewed 30 times. For the vigilance task, the ball and sponge pictures were included in an additional 16 trials. Trials in each category and those of the vigilance task were presented in a randomised order.

There were two viewing postures. For the right-hand forward posture the right hand rested close to the screen with the body rotated approximately 45° away from the screen towards the left. The head was maintained directly facing the screen. For the left-hand forward posture the left hand rested close to the screen with the body rotated approximately 45° away from the screen towards the right. Again, the head was maintained facing directly towards the screen (see Figure 3.1B). The order of the first and second postures was counterbalanced across participants. For each posture a block lasted approximately 15 minutes and participants were offered a short break after 100, 200, 300 and 400 trials.

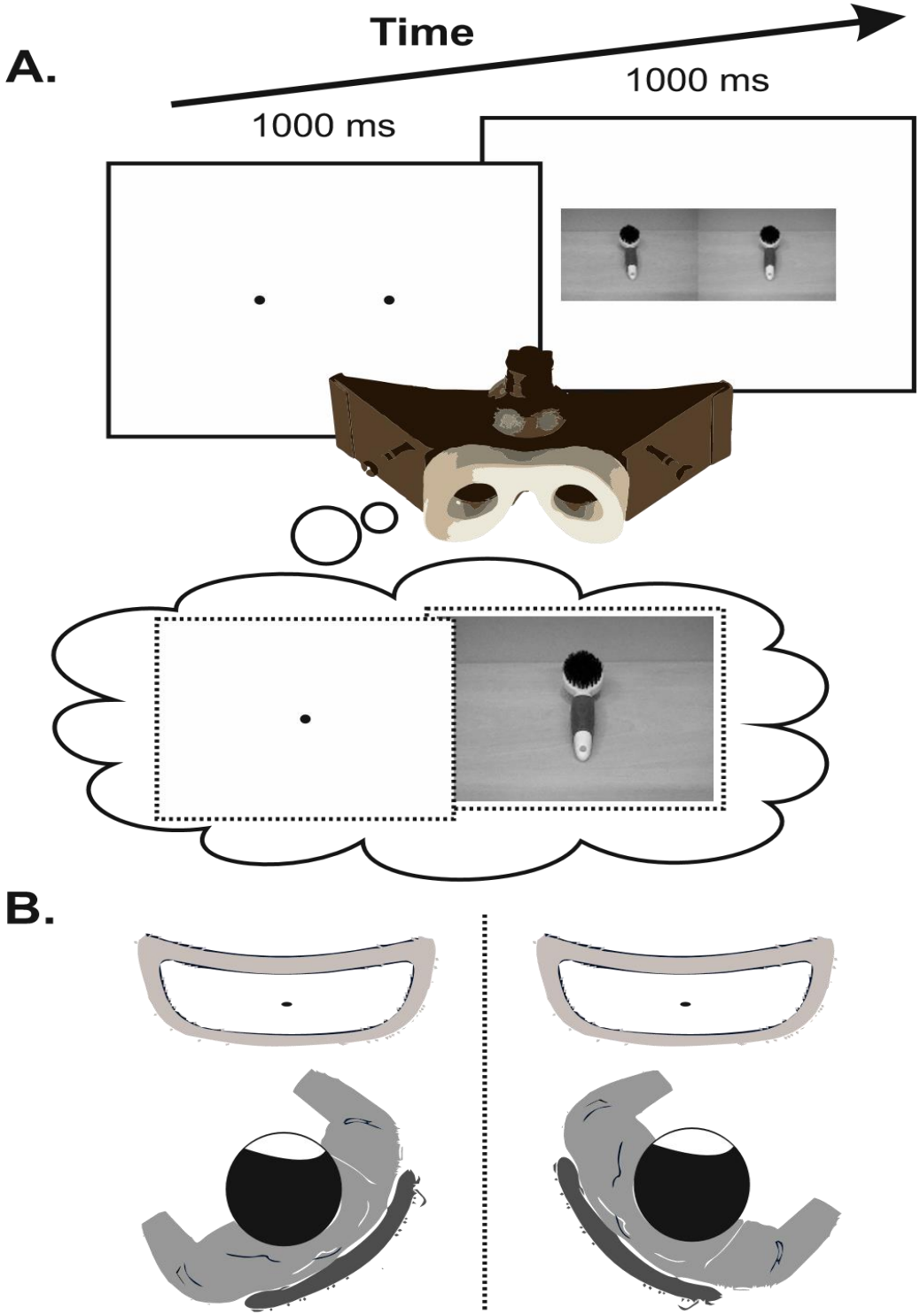


Figure 3.1. Schematic of Experimental Methods. **A.** Example trial from the EEG paradigm. Here a whole-hand grasp object is displayed (both in stereo, as presented, and as perceived through the stereoscopic viewer, with left and right images fused). **B.** Schematic showing Posture 1 with right (dominant) hand closer to the screen and Posture 2 with left hand closer to the screen; in each case the head is maintained directly facing the screen.

3.2.4 EEG Measurement and Analysis

A 64-channel electrode cap was fitted to the participant's head with the ground electrode at position AFZ and the reference electrode at position FCZ. An additional vertical electro-oculogram electrode was placed below the left eye. Electrode impedance was kept below 20 k Ω and recorded at a sampling rate of 1000 Hz. Recording and pre-processing of the EEG data were performed with a BrainAmp DC amplifier and the BrainVision Recorder software (Brain Products, Herrsching, Germany).

For the ERP analysis the data were band-pass filtered offline with high-pass frequency of 0.1Hz and a low-pass frequency of 35Hz and re-referenced to averaged mastoids. Data were segmented into epochs of 1500ms, from 500ms prior to stimulus onset to 1000ms after stimulus presentation. The Gratton and Coles method (Grattan, Coles, & Donchina, 1983) was used for ocular correction, and baseline correction was applied using a window from 100ms to 0ms before the stimulus. Epochs were also excluded automatically if any values exceeded a threshold of ± 100μV, resulting in a rejection rate of ~10%. Based on inspection of averaged data, peak event-related potential (ERP) amplitudes for the posterior N1 component were computed at the PO3 and PO4 electrodes and the anterior component at the F1 and F2 electrodes, both in the interval 100ms to 200ms after stimulus onset. Immediately after the clearly observable N1 ERPs the EEG traces varied considerably in the different stimuli categories and across participants. Consequently, for the anterior N2 component at the F1 and F2 electrodes a peak-to-peak measurement was taken from the most positive preceding peak (P2) to the most negative following peak (N2). The P2

was calculated as the local peak between 160ms and 260ms after stimulus onset and the N2 was calculated as the local peak between 235ms and 360ms after stimulus onset. For each individual participant's set of data an earlier P2 peak corresponded with an earlier N2 peak and a later P2 peak corresponded with a later N2 peak. The aim was to standardize the measurement between categories by observing the amplitude between the peaks.

Repeated measures 2x2x3 ANOVAs were carried out assessing differences in N1 and N2 amplitudes with the following within-subject factors: posture (left- and right-hand forward), hemisphere (left and right) and the three stimulus categories (power-grip objects, precision-grip objects and no object). The Greenhouse-Geisser correction was used to correct for violations of sphericity.

3.3 Results

Analyses focused on both the prominent N1 negative component, whose time-course varies across the scalp from anterior to posterior, and the anterior N2, described by Proverbio et al. (2011) and previously inferred to reflect the presence or absence of an affordance.

3.3.1 The N1 Component

A distinct N1 component was observed. At posterior sites, PO3 and PO4, (not shown) the posture by hemisphere by stimulus category (2x2x3) ANOVA revealed no difference between postures, nor between hemispheres, nor stimulus categories and there were no significant interactions. In fact, $F<1.0$ for

all effects involving stimulus categories.[1] Mean microvolt stimulus category differences were: between power grip and precision grip 0.39μV (SD = 2.30), between power grip and no object 0.14μV (SD = 2.51) and between precision grip and no object 0.53μV (SD = 1.51).

At anterior sites, namely electrodes F1 and F2, (see Figure 3.2, earlier greyed region) the posture by hemisphere by stimulus category (2x2x3) ANOVA revealed a main effect of hemisphere $F(1, 28) = 9.023$; $p = .006$, $\eta p^2 = .244$ and a main effect of stimulus category $F(2, 56) = 4.949$; $p = .020$, $\eta p^2 = .150$. T-tests showed no significant differences between power-grip objects and precision-grip objects, $p = 1.00$, and no differences between power-grip objects and the empty desk, $p = .254$. There was, however, a significant difference between precision grip-objects and empty desk, $p = .001$. There was no main effect of posture. There was also a significant interaction between posture and hemisphere $F(1, 28) = 7.032$; $p = .013$, $\eta p^2 = .201$; pairwise follow-ups showed significant differences between hemispheres only in the right-hand forward posture, $p = .001$. All other interactions involving stimulus categories, were not significant: posture x hemisphere x stimulus category, $p = .329$; posture x stimulus category, $p = .337$; hemisphere x stimulus category, $p = .234$.

[1] Actual means, 1.16μV (SD = 3.88) for the power-grip object, 1.55μV (SD = 2.64) for the precision-grip object and 1.01μV (SD = 2.38) for no object.

3.3.2 The N2 Component

Turning to the N2 ERP component: As can be seen in Figure 3.2 (later greyed region), for posture 1 (i.e. right hand forward) there is an enhanced N2 in both object categories compared to the no object category. This difference between categories is far less pronounced in posture 2, particularly in the left hemisphere. A posture by hemisphere by stimulus category (2x2x3) ANOVA showed significant main effects of hemisphere, $F(1, 28) = 9.918$; $p = .004$, $\eta p^2 = .262$, and stimulus category, $F(2, 56) = 24.091$; $p < .001$, $\eta p^2 = .462$. All t-tests between stimulus categories showed significance; $p = .026$ between power grip objects and precision grip objects while $p < .001$ between each object category and the empty desk.

Of particular interest for the experimental design, the interaction between posture, hemisphere and stimulus category was marginally significant, $F(2, 56) = 2.936$; $p = .081$, $\eta p^2 = .095$. However, there was a clear directional prediction regarding this interaction (that the posture by stimulus category interaction should be enhanced in the left hemisphere), which was supported by the pattern of means (see Figure 3.2). Although F tests are strictly speaking one-tailed, an ANOVA interaction can be considered a form of “multi-tailed” test, as no directionality of effect is specified (see Howell, 1997, pg. 154, for this argument in the context of another multi-tailed test, the χ^2 test of association). With under half of all possible interaction data patterns conforming to the a priori expectation, it appeared justifiable to use an alpha value of 0.1.

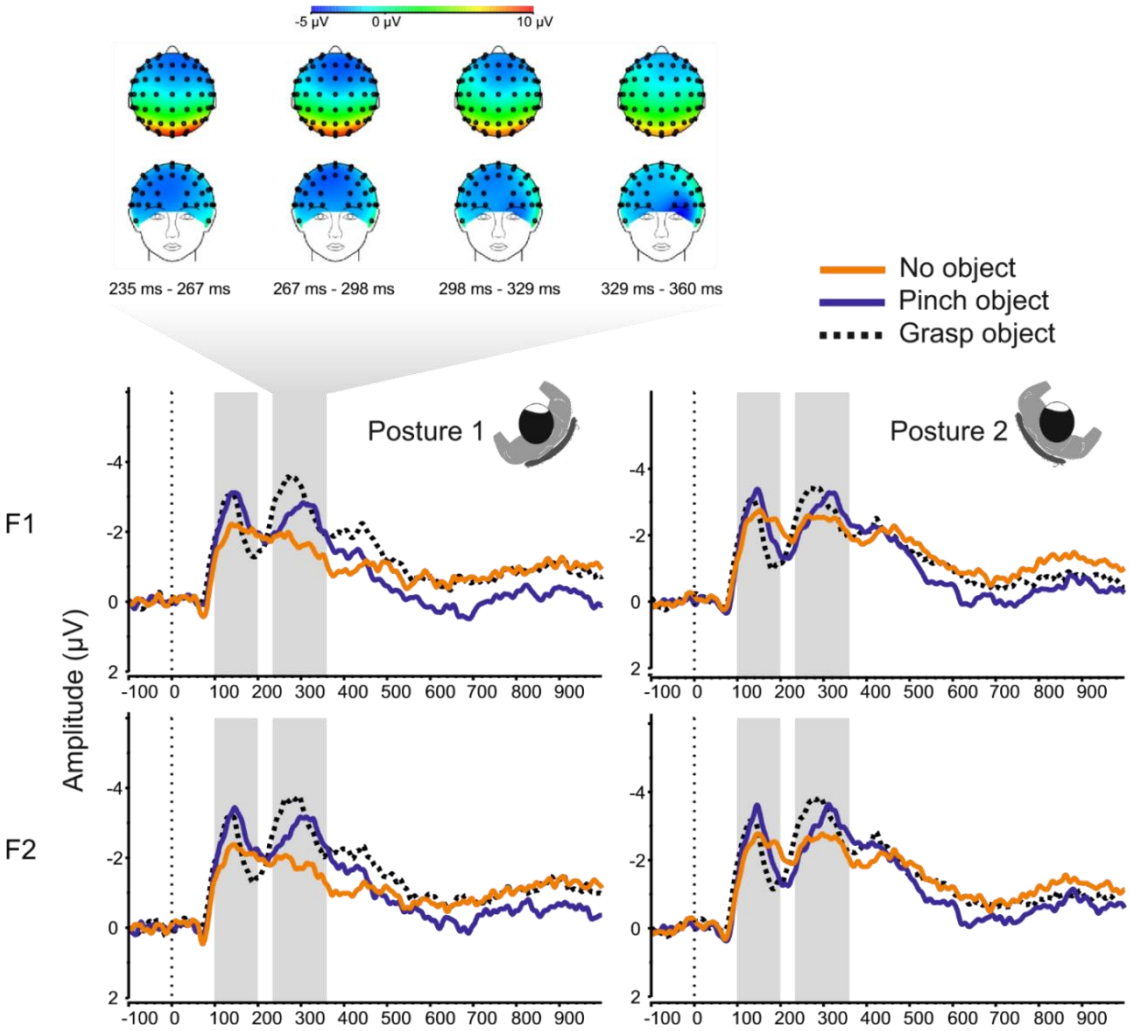


Figure 3.2. Grand averaged F1 and F2 electrode traces for both Posture 1 (right hand forward) and Posture 2 (left hand forward). Shown in grey shaded areas are the N1 component between 100ms and 200ms after stimuli onset and the N2 component between 235ms and 360ms after stimuli onset. ERPs are depicted by a broken black line for power grip objects, a blue line for precision grip objects and an orange line for the empty desk (no object). Head maps show voltage across the scalp with greatest negativity in blue and relate to grasp objects in Posture 1.

Hence, the interaction between posture, hemisphere and stimulus categories was considered meaningful, and a further posture by stimulus category (2x3) ANOVA was conducted separately for each hemisphere in order to follow it up.

For both hemispheres the difference between stimulus categories was significant (right hemisphere, $F(2, 56) = 24.229$; $p < .001$, $\eta p^2 = .464$; left

hemisphere, $F(2, 56) = 21.769$; $p < .001$, $\eta p^2 = .437$). For the right hemisphere (F2 electrode) the posture by stimulus category interaction was not significant; $p = .285$. Critically, for the left hemisphere (F1 electrode) there was a significant interaction between posture and stimulus category, $F(2, 56) = 3.201$; $p = .048$, $\eta p^2 = .103$. The interaction reflected a greater modulation of the N2 by object condition for the right-hand forward posture than for the left-hand forward posture and pairwise follow-ups showed that both of the object categories differed from each other, $p = .001$ and both object categories differed from the no object category $p < .001$ in the right-hand forward posture.

However in the left-hand forward posture there was less overall modulation by object category (driving the interaction effect in the posture by stimulus category ANOVA); while both object categories still differed from the no object category $p < .001$, there was no significant difference between the two types of object categories, $p = .318$.

3.3.3 Other ERP Components

Proverbio et al. (2011) additionally observed a peak between 750ms and 850ms over prefrontal sites which they described as late positivity and which produced a significantly larger amplitude for non-tools compared to tools. In addition, the P300 ERP over centro-partietal electrodes also produced significantly larger amplitudes for tools compared to non-tools. These effects were also sought. However, no discernible ERP was found near 800ms. For the P300 ERP, recordings from C1, C2, CP1 and CP2 electrodes were analysed as these corresponded most closely with the CCP1h, CCp2h electrodes used by

Proverbio et al. (2011). Their P300 component was found between 550ms and 600ms, but observing the current EEG data, the component was not clearly discernible, so it was not investigated further.

3.4 Discussion

This experiment sought to provide further ERP evidence regarding the timing of affordances, by manipulating participants' posture in relation to the objects being viewed. Participants were presented with either power grip or precision grip objects on a desk, or with an empty desk, and positioned their bodies so as to vary whether those objects could be reached easily with the dominant hand (while holding visual stimulation constant). Brain activity was recorded while they observed a random sequence of stimuli at a rate of 0.5 Hz. This experiment made primes more functionally relevant by providing stereo depth cues, and demonstrated a robust affordance-based brain response under these conditions (c.f. Makris et al., 2013).

The resulting significant interaction between posture and stimulus category, found in the dominant left-hemisphere N2 ERP component of right-handed participants, demonstrates that the N2 reflects object affordances, which should be affected specifically by the participants' position in relation to the stimuli. Indeed, the N2 component even appeared to distinguish between the types of grasp or grip that would be appropriate for the particular object being presented (rather than simply distinguishing between graspable objects and empty desks). The affordance effect was present in the left-hand forward posture, but to a lesser extent as differences were found only between objects (of either type)

and the empty desk. Although there was a significant effect for stimulus category in the right hemisphere, there was no significant interaction between posture and stimulus category like the one obtained in the left hemisphere. It might have been expected that in the right hemisphere the N2 component would be significantly greater in the left hand forward posture. However, as participants all had right hand dominance, these results substantiate the theory that it is the dominant hand positioned close to an object that enhances affordance effects.

These results complement and extend those of Proverbio et al. (2011) and Proverbio (2012) who investigated EEG markers for automatic object-action priming. In their work, pictures of objects affording action were contrasted with pictures that did not afford any actions, and effects were found in the N2 (and later), with a swLORETA analysis linking this effect to motor regions of the brain.

The posture manipulation in this experiment changed the functional relevance of objects without changing their visual properties, and therefore these data strengthen their finding. If significant differences had simply been shown between the object conditions, it might be argued that the gross visual differences between a large, graspable object, a small, forefinger and thumb pinchable object and an empty desk, could account for the ERP differences without implying that functional, motor properties of objects were the primary cause.

In addition to ruling out visual effects via the logic of the expermental design, the inference of a motoric effect was also strengthened by observing the visual N1 ERP component between 100ms and 200ms after stimulus onset. Interestingly, for both postures, at the posterior PO3 and PO4 electrodes, the N1 ERP component had a very similar peak voltage at very similar latencies for all stimulus categories – power-grip objects, precision-grip objects and no object. Hence, in the data, there appears to be little detectable difference between stimulus-evoked visual activity in parietal-occipital regions between 100ms and 200ms after stimuli onset. However, anteriorly (at the F1 and F2 electrodes) this component did show differences in peak values between the stimulus categories. For both hemispheres, precision grip objects produced a significantly greater negative peak than the empty desk. The N1 peak produced by the power grip objects was also larger (althought not significantly) than that produced by the empty desk (see Figure 3.2).

These findings may be due to early motoric discrimination of picture content. Evidence from previous experiments suggests that the anterior N1 is produced by motor responses (Vogel & Luck, 2000). In their study, a first experiment incorporated a button press response while the second asked participants to just keep a count of the number of stimuli presented. In the first experiment a large anterior N1 effect was observed. In the second, this effect was diminished. The researchers hypothesised that the anterior N1 ERP in the first experiment was due to an overlap of preparation for a motor response with the stimulus-elicited response. As a footnote in the article, Vogel and Luck (2000) confirmed completion of further experiments to control for motor-related overlap. In one they instructed participants to respond at the same speed for simple and

complex tasks and in the other the SOA was varied to reduce anticipated motor responses. In both of these the anterior N1 was eliminated but the posterior N1 remained. Thus prior research would suggest that while posterior N1 activity relates to purely visual properties, the anterior N1 is influenced by motor preparation. It is therefore striking that in the current experiment, essentially no anterior N1 peak was observed for an empty desk, with this component emerging only when objects were viewed despite no requirement to actually respond to them. This is a very early ERP component and therefore it is possible that full affordance properties have yet to be completely processed. Indeed, there was a (non-significant) trend towards an interaction between stimulus category and posture even in the anterior N1. In the experiment the subsequent N2 component, particularly the significant left-hemisphere interaction between posture and stimulus category, serves to confirm motoric involvement and, consequently, the presence of an affordance.

This is the first EEG study to evidence affordances via changes in the functional relevance of graspable objects. In a recent TMS study a computer generated 3D room was used (presented on a 2D display without stereo depth; Cardellicchio et al., 2011) to vary whether stimuli could be reached or not. The stimuli consisted of either a mug with a handle (graspable object) or a cube (non-graspable object) on a table. TMS pulses were delivered to obtain responses from the first dorsal interosseous and the opponens pollicis hand muscles, both of which are activated when grasping a mug handle. The mug and the cube were shown separately in two conditions. Each was shown positioned within reachable space and also further away, in non-reachable space. Electromyographic (EMG) recordings showed that when it was observed

within reachable space, the mug produced significantly greater MEPs than when it was observed in non-reachable space. No such effect occurred with the cube stimulus. From this result, the authors suggested that the affording properties of an object are able to induce motor representations only when the object is appropriately positioned within the observer's reach.

In the current study, while each 3D object appeared in exactly the same spatial position, the posture of the observer was altered, effectively placing either the dominant (right) hand closer to the object (Posture 1) or the non-dominant (left) hand closer (Posture 2). Lateralized affordance bias from the objects themselves was eliminated as the objects were displayed with any handles presented centrally. The results, showing a greater N2 ERP component for object stimuli compared to the empty desk, but particularly when the object could be manipulated with the dominant hand, corroborate and advance those of Cardellicchio et al. (2011). Although the objects were all effectively positioned within reachable space, the results relate enhanced affordance properties particularly to the close proximity of the dominant hand. This early affordance effect also conforms with other studies showing greater MEP sizes around 200ms after stimulus onset when assessed via handle orientation (Buccino et al., 2009) and at 300ms after stimulus onset (but not later) when assessed via grip congruence (Makris et al., 2011, 2013).

The result is at odds with some previous findings, e.g. Wilf, Holmes, Schwartz, & Makin (2013). This group sought to dissociate affordance effects and spatial effects (Simon, 1969) and determine whether there was an interaction between them. Their stimuli were pictures of graspable and non-graspable objects

projected to either the left or right side at around shoulder height. The sizes and spatial properties of the images were matched, e.g. an elephant and a mug were depicted as the same size and had similar outline shapes. The task was to make a lateralised response to determine if the objects contained metal, irrespective of whether they could be grasped, for example, a right-hand response for metal and a left-hand for non-metal or vice versa. Wilf et al. (2013) analysed muscle activity and obtained both an effect of spatial compatibility (i.e. enhanced left-hand responses for objects on the left and vice versa) and an effect of affordance (i.e. enhanced responses for graspable objects). Importantly, there was no interaction between spatial compatibility and affordance, implying that the latter effect emerged for objects both near and far from the responding hand. However, it is worth noting that their manipulation of object position would still have left objects reachable with either hand in relative comfort. By contrast, the current posture manipulation may have been more effective in modulating action tendencies for the dominant hand as it would have required considerably more effort if participants had been required to act with the more distant hand.

3.5 Conclusion

Passively observing manipulable objects from different postures modulates EEG activity in a manner consistent with the existence of automatic affordances within the motor system. Here it has been shown that, across the three stimulus categories, the evoked ERP N2 component modulates differently between participants' postures, i.e. depending upon whether the dominant or non-dominant hand was closer to the object. It has also been shown that this is not

purely a visual effect, both through the logic of the design and by examination of the N1 component. Prior research has suggested that the anterior N1 component is enhanced by motor preparation. As only objects requiring a power or precision grip produced the N1 component at anterior sites and the empty desk did not, this result also provides suggestive new evidence for affordance. Hence it is proposed that affordances generated by 3D objects may become active within 300ms after stimulus onset, consistent with other evidence from EEG and TMS experiments.

In the following chapter, complementary evidence was sought from another neuroimaging technique with greater ability to (specifically) localise the motor system.

Chapter 4

TMS study to detect affordance activity in healthy participants

4.1 Introduction

Visually observing an object can potentiate motor planning even when there is no intention to act. J Gibson, in his seminal work in 1977 introduced the term affordances, suggesting that just by viewing an object we perceive actions of how to use it. To investigate this ecological approach, various types of objects and tools have been trialled in behavioural, EEG, fMRI and TMS studies, allowing analysis of response times, neuronal activity and MEPs when subjects have viewed action-related items (e.g. Bartoli, Maffongelli, Jacono, & D'Ausilio, 2014; Cattaneo et al., 2005; Galpin et al., 2011; Grèzes et al., 2003; Roberts & Humphreys, 2010; Vainio et al., 2014) and also stimuli not expected to elicit affordances (Buccino et al., 2009; Cardellicchio et al., 2011; Creem-Regehr & Lee, 2005; Galpin et al., 2011).

Transcranial magnetic stimulation (TMS) can be used to trigger motor evoked potentials (MEPs) which index the state of the corticospinal motor system (Austin & Rothwell, 2017; Rossini et al., 2015; Schambra et al., 2003). TMS provides a powerful tool for investigating automatic motor priming, because the MEPs it evokes have a clearly defined locus/origin in the motor system, and allow the experimenter to interrogate its state with high temporal resolution.

Previously, research has shown greater MEPs for the first dorsal interosseous (FDI) muscle when TMS pulses are delivered to the contralateral motor cortex at specific time-points after the presentation of a manipulable stimulus (compared to control stimuli). Different groups found different optimum times, e.g. 120ms after stimulus presentation (Franca et al., 2012) and at 300ms after stimulus presentation (Makris et al., 2011).

Several TMS studies of affordance have now been reported. As mentioned in Chapter 3, Cardellicchio et al. (2011) found enhanced MEPs in opponens pollicis (OP) and FDI when a graspable object (a mug) appeared in reachable space. They delivered a TMS pulse of 120% RMT at 50ms after stimulus onset.

Investigating priming for precision grip only, Franca et al. (2012) carried out a TMS study with physical objects presented in an open-sided box within participants' peripersonal space. Objects were chosen that would require a thumb and forefinger precision grip so that FDI and opponens pollicis (OP) muscles would be activated. They also monitored the abductor digiti minimi (ADM) which is activated when using a whole hand power grip. Objects were presented individually and there was a second, 'no-object', condition where the box remained empty. TMS pulses were delivered at 120ms, 150ms and 180ms after stimulus onset. At 120ms stimulation, FDI MEPs were significantly greater for object present compared to no object category.

Similarly, Buccino et al. (2009) stimulated left motor cortex with TMS pulses delivered at 200ms after stimulus onset. Stimuli were jugs or mugs in categories depending on whether the handle was whole or broken and whether

the handle was orientated towards the right or left. MEPs were significantly greater for both OP and FDI muscles for objects with whole handles orientated towards the right. There were no significant differences between the muscles, but, again, these are both activated during a precision grip (rather than a power grip).

McNair, Behrens, & Harris, (2017) recorded from FDI only when delivering TMS pulses at 250ms after stimulus onset. Designed as an attentional blink paradigm, one presentation was the target object for 500ms; the other was target presentation for 83ms before a backward mask stimulus for 83ms. After either presentation, a fixation cross appeared for 500ms and then a picture of all 20 graspable and non-graspable objects (i.e. an identification task to allow assessment of the effectiveness of masking). Participants had to decide whether the target object was graspable or non-graspable. MEPs for the FDI were significantly greater for graspable objects in both presentation conditions. The result implicates an affordance effect even without clear awareness of the object, which suggests that affordances are quite automatic.

Bartoli et al. (2014) investigated two muscles; abductor pollicis brevis (APB) and ADM. The paradigm began with an adaptation phase for 40s; a video of a hand repeatedly making the same power grip or making the same precision grip. Objects were then presented that would match the adaptation hand (congruent for affordance) or not; either requiring a precision grip that would utilize APB or a power grip, utilizing ADM. 150ms after onset of the picture stimulus a TMS pulse was delivered over the left M1. A significant affordance x congruency interaction was obtained for both APB and ADM muscles. Post-hoc analyses

revealed significantly higher mean z-scored MEPs for the congruent power adaptation and tool affording a power grip compared to the congruent precision adaptation and precision-grip tool for the ADM. The reverse was true for the APB; higher scores for congruent precision adaptation and tool affording precision grip compared to the power adaptation and power-grip tool. However these results only confirmed differences between *congruent* conditions. For the ADM there was no significant difference whether participants viewed the power-grip or the precision-grip tool after the power adaptation. Equally, for the APB there was no significant difference whether participants viewed a power- or precision-grip tool after a precision adaptation. Participants were also required to judge whether the hand was congruent for object and to respond with a left hand button press.

Unlike these experiments, Makris et al. (2011, 2013) observed separate motor priming effects in separate muscles, each active for different types of grip, without participants being required to make a physical response. In 2011 they used two-dimensional colour photographs in three stimuli categories; 'pinchable' objects that would require a precision grip, activating the FDI muscle, 'graspable' objects that would require a power grip, activating the abductor digiti minimi (ADM) muscle and 'neutral' objects that would not require any obvious hand action. TMS pulses were delivered over the contralateral primary motor cortex (M1) to cause simultaneous MEPs in both the FDI and ADM. TMS pulses delivered at 300ms after stimulus presentation produced results revealing action specificity; significantly larger MEPs occurred in FDI for precision grip objects compared to power grip objects, with, if anything, the opposite pattern for ADM MEPs. In the 2013 experiment, physical objects were presented rather than 2D

images. For both FDI and ADM, objects that were congruent for the type of grip for each muscle produced significantly larger MEPs. This result occurred when TMS pulses were delivered at 300ms and at 450ms after onset of stimulus.

4.2 Current Study

Previous work suggests a motor priming effect, but different studies demonstrate this in a more (or less) specific way (e.g. Bartoli et al., 2014; Cattaneo et al., 2005; Galpin et al., 2011; Grèzes et al., 2003; Roberts and Humphreys, 2010; Vainio et al., 2014). For studies utilising TMS, some studies show change in MEPs for a single muscle, without recording from other muscles. For example, McNair et al. (2017) recorded from just the FDI. This could be a very non-specific form of priming (e.g. the entire motor system is being primed). Some studies are more specific, either recording other, irrelevant, muscles and showing that they are not similarly affected (e.g. Franca et al., 2012), or showing a differential effect for different muscles in response to different kinds of object (e.g. Makris et al., 2011; 2013).

However, if these really are affordances, they should be influenced not just by the type of object, but also by our ability to interact with it. Therefore, the current experiment incorporates a new, novel manipulation of posture. Combining a posture manipulation with action priming in different muscles may produce more compelling evidence of affordances. Theoretically, a posture manipulation placing the dominant hand close to the object would enhance corticospinal motor priming. Hence, the delivery of TMS pulses would generate greater affordance-related modulation of MEPs from muscles on the dominant hand

compared to placing the non-dominant hand near the object. While one previous TMS study has investigated the effect of changing the functional relevance of objects (by placing them within/outside of reach space; Cardellicchio et al., 2011), no TMS studies have included this kind of manipulation in a design additionally seeking differential priming effects for different muscles.

The current study was also planned with the expectation that results would be similar to those previously reported from this lab (Makris et al., 2011) as the same Magstim stimulation equipment and cathode ray tube (CRT) monitor would be used. Nevertheless, in an attempt to elicit the most natural affordance activity and resulting EMG when viewing stimuli on a computer screen, instead of two dimensional photographs being observed (Makris et al., 2011), three dimensional (3D) photographs were taken and then viewed on the CRT monitor through a stereoscopic viewer (c.f. the real objects used in Makris et al., 2013). It was considered that this new approach of showing objects in three dimensions might better reveal their intrinsic properties, thereby invoking greater differences in the two muscle responses.[2]

[2] The study was also designed to run in parallel with a similar EEG experiment (already described in Chapter 3) and a second objective was to correlate each individual participant's own TMS data with their EEG data. It was hypothesised that across volunteers greater MEP priming effects (i.e. greater MEPs from the FDI when viewing precision grip objects than power grip objects, and vice versa for the ADM) would correlate with greater enhancement of the EEG N2 event related potential (ERP) when objects were viewed (compared to an empty desk). This hypothesis was abandoned when it became apparent that the TMS experiment was not yielding the anticipated motor-priming effects; see results, below.

4.3. Materials and Methods

4.3.1 Participants

20 participants were initially recruited from inside and outside of the University through City, University of London Sona System online research recruitment (9 male, 11 female, mean age 28 years 1 month, SD 5 years 11 months). Each was given full information regarding the safety aspects of TMS at least one day prior to attending. They also completed a health screening questionnaire immediately prior to the session to confirm suitability for this form of monitoring brain activity (example questionnaire in appendix A). All had normal or corrected-to-normal vision with no history of neurological illness and all were right-handed as verified by the Edinburgh Handedness Inventory, adapted from Oldfield (1971). The study was approved by City, University of London Ethics Committee and participants gave written consent. Volunteers were paid £8 per hour for their time with sessions lasting approximately 2 hours. However, soon after starting the session, two volunteers were excluded from the experiment (but still paid) due to having a very high TMS threshold, as it would not have been feasible to obtain the necessary output from the stimulator to carry out the experiment. At the end of the experimental session, participants were given a debrief form confirming the number and frequency of pulses administered and requesting feedback for any adverse effects during the experiment. No participant recorded any such effects (sample form in appendix B).

4.3.2 Stimuli

A subset of independently rated 3D photographs of 40 objects (full details of assessment of stimuli is reported in Chapter 3) was chosen which contained good exemplars of objects affording either a forefinger and thumb precision grip or a whole hand power grip (i.e. consistently rated “always” for the relevant grip and predominantly rated 2/2 on a familiarity scale). For the experiment, these stimuli were used to construct two object stimulus categories. The first consisted of one picture of each of five objects, which would normally be held in a precision grip (tweezers, drawing pin, button, wedding ring, and paperclip). The second consisted of one picture of each of five objects which would normally be held in a power grip (hairbrush, glass, mug without handle, liquid soap container and knife). Because MEPs are spatially specific regarding the form of action preparation they measure, the less relevant object category (e.g. power-grip objects when considering MEPs from FDI) formed a control for the more relevant category (e.g. precision-grip objects). Hence the no-object category, used in the EEG experiment reported in Chapter 3, was omitted to reduce the number of experimental trials.

4.3.3 Design and Procedure

Participants were seated in front of a mounted stereoscope, approximately 45cm from a CRT monitor refreshing at 100 Hz. Left-eye and right-eye images were displayed side by side, but presented only to their respective eyes via the mirror stereoscope (Stereo Aids, Australia) (Figure 4.1). Initially, participants were allowed time to adjust the viewer so that they observed a single object in three dimensions. For this calibration, two objects, a tennis ball and a

dishwashing sponge, were presented in alternation. These two objects became targets for a subsequent vigilance task.

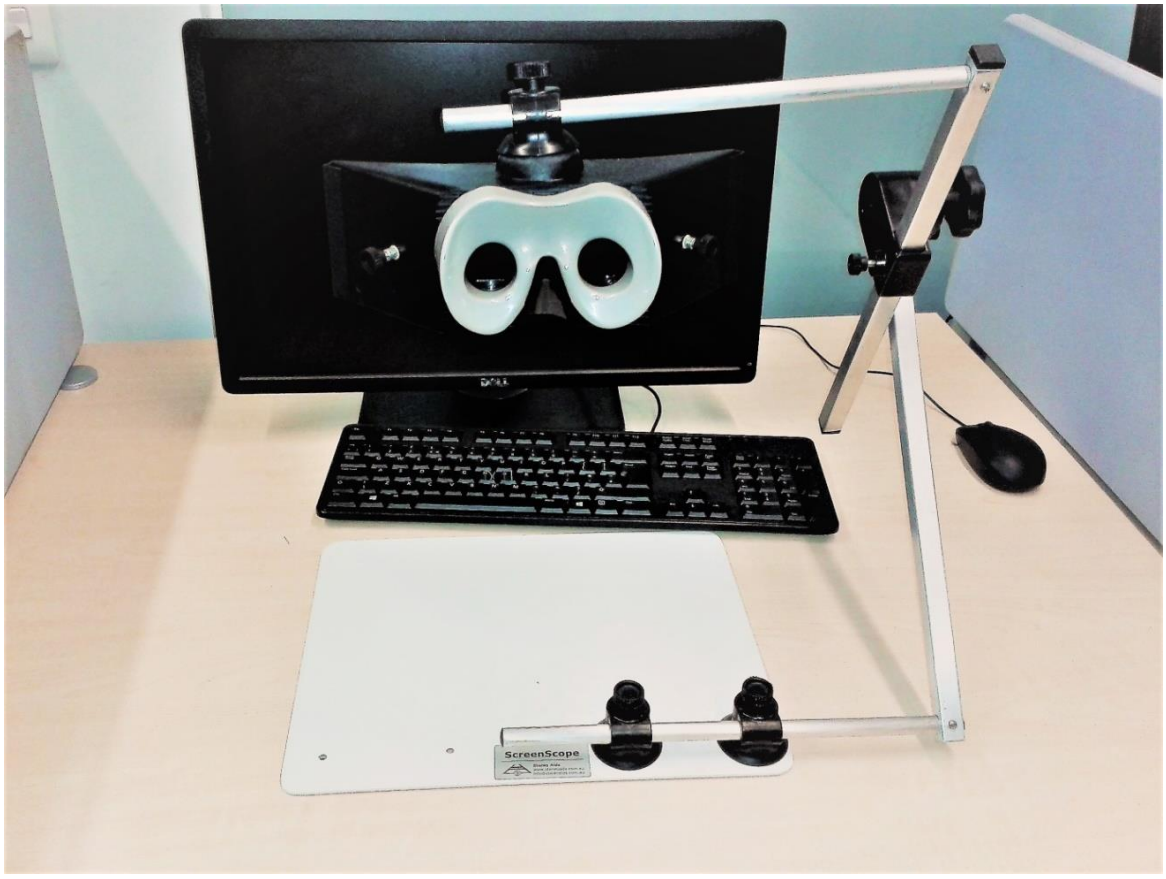


Figure 4.1. Height and vision adjustable 3D viewer positioned in front of a computer screen (note: not the CRT monitor used in this experiment).

There were two viewing postures. For the right-hand forward posture the right hand, with EMG electrodes attached, rested close to the screen with the body rotated approximately 45° away from the screen towards the left. The head was maintained directly facing the screen. TMS pulses were delivered to the primary motor cortex of the left hemisphere. Electromyography (EMG) recordings were acquired from the electrodes. For the left-hand forward posture the left hand rested close to the screen with the body rotated approximately 45° away from the screen towards the right and the head was maintained facing directly

towards the screen. Again, EMG recordings were acquired from the electrodes on the right hand, now resting on the participant's lap, and TMS pulses were delivered to the primary motor cortex of the left hemisphere. The order of the first and second postures was counterbalanced across participants.

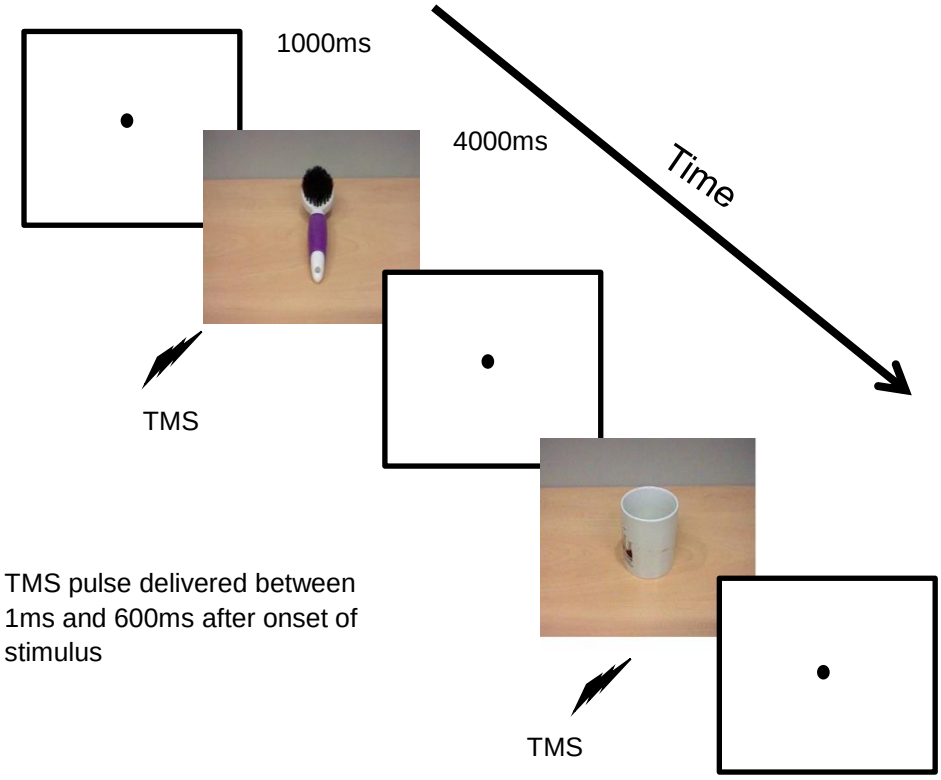


Figure 4.2. Schematic diagram of TMS paradigm (two trials). Objects appeared to participants in 3D.

The TMS paradigm consisted of the objects on screen for 4 seconds, being preceded by a fixation dot for 1 second (Figure 4.2). There were 216 trials per block, with 100 objects in each of the two categories of either precision grip or power grip, shown in random order. Within each category, each of the 5 object stimuli was shown 20 times. Participants were not required to respond to these objects, but instead had to say aloud the names of the two calibration items when they appeared. These were randomly interspersed within each block in an additional 16 trials. To determine the timing of any affordance, the TMS pulses

were given randomly at different times, ranging between 1ms and 600ms after onset of stimuli. With 200 pulses for each type of object, delivery timings were also separated into four time windows with 50 pulses in each; 1ms to 150ms (TW1), 151ms to 300ms (TW2), 301ms to 450ms (TW3) and 451ms to 600ms (TW4). To prevent fatigue, participants were offered regular breaks after every 20 trials and when changing position for the second posture.

4.3.4 EMG Recording

Two surface Ag/AgCl EMG electrodes (22 x 28 mm, part No.SX230FW, Biometrics Ltd., Ladysmith, VA) were placed on the right hand, approximately 2–3 cm apart over the ADM muscle and a nearby reference site (just above the styloid process of the right ulnar). Two other electrodes were similarly placed to record from the FDI muscle of the same hand with further ground electrodes attached to the wrist. EMG (band-pass filtered 20–450 Hz) was collected at 1000 Hz via a 13-bit A/D Biometrics Datalink system (version 7.5, Biometrics Ltd.) and stored on a second dedicated PC. Digital data were exported and analyzed offline using MATLAB (The Mathworks, Natick, MA). To achieve the greatest number of usable MEPs, the EMG was also sent to a speaker to detect separate FDI and ADM muscle activity which might represent pre-activation and render the MEP invalid. Two individual speakers (one for each muscle) served as a prompt for participants to relax the relevant muscle.

4.3.5 TMS Protocol

Pulses were applied using a 70-mm figure-of-eight coil (external casing diameter ~90 mm for each loop) connected to a Magstim Rapid^2 biphasic

stimulator (The Magstim Co. Ltd., Whitland, UK).The coil was held tangentially to the skull, over the optimal spot at the contralateral hemisphere, to elicit MEPs in both the ADM and FDI (the hand "motor hotspot") with the handle pointing backward/laterally approximately midway between the sagittal and coronal planes. Prior to the main experiment, each individual's resting motor threshold (RMT) was obtained. To detect the hotspot, first the coil was placed on the scalp above the left primary motor cortex. (The position of this part of the cortex was judged from experience by the experimenter). The coil was then moved by approximately 1cm in each direction until the greatest MEPs were produced. During this process, stimulation began at 30% of the stimulator's output and was increased by 5% increments until MEPs were reliably recorded. Then the output was decreased in 1% steps. The RMT was observed and noted as the lowest stimulation value when at least 5 out of 10 consecutive TMS pulses produced MEPs from both the FDI and ADM of 50μV or more while the participant's hand was fully relaxed. Intensity of pulses was then set to around 110–120% of RMT in order to elicit MEPs of around 1 mV amplitude in both the ADM and the FDI. Stimulation frequency never exceeded 0.2 Hz. After the hotspot and RMT were determined, no more than 432 pulses were administered during the experimental session.

4.3.6 EMG Measurement and Analysis

Each individual MEP was verified using customized MATLAB software allowing semi-automatic rejection for pre-activation. The program showed a time-window to recognise an MEP between 20ms and 40ms after the TMS pulse. In Figure 4.3 the upper boxes indicate activity of the FDI muscle and the lower

indicate ADM activity. The TMS pulse is shown in yellow and the 20ms time-window is indicated (in a trial with no muscle pre-activation) by green markers. The time zero at the bottom of the large boxes indicates the onset of the visual stimuli and the right hand boxes show that throughout the 200ms prior to the TMS pulse there was no activity recorded from either muscle with peak-to-peak EMG excursion of 50μV (so no deflection in either direction > 25μV). This means that the MEP was acceptable because it was not influenced by prior muscle activity.

MEPs produced from stimulation of the FDI always tended to be greater than those produced when the ADM was stimulated. This is likely to be the case because the FDI is more regularly used in everyday activities and thus better represented in M1, so the intensity of the stimulation, although the same for both muscles, caused a larger MEP from the FDI. Therefore z-scores were obtained, expressing MEP size relative to the mean (and normalised by the standard deviation) of MEP magnitudes for each muscle for each participant. To limit the influence of amplifier saturation (which caps MEP size) and misplaced

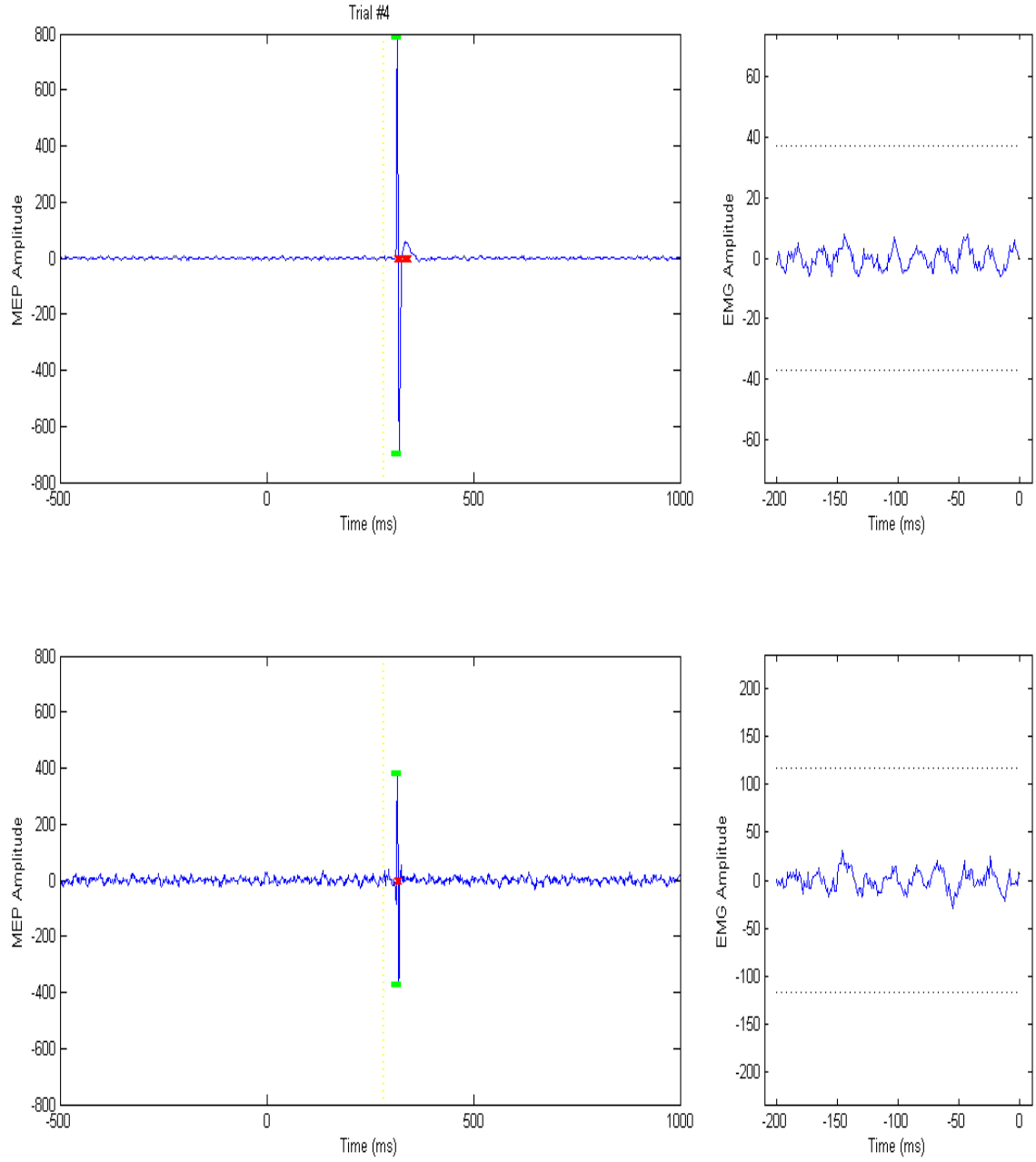


Figure 4.3. Example of EMG recording for FDI (top left) and ADM (bottom left). Within the left hand boxes, 0 on the time axis represents the stimulus onset, the dotted yellow line represents the TMS pulse and the MEP is contained within the green markers. Right hand boxes show that during the 200ms prior to the pulse, there was no spontaneous muscle activity that would adversely affect the EMG recording.

TMS pulses (which lead to absent MEPs) the medians of each participant's z-scored MEPs within each cell of the design were calculated and used in the inferential statistical analysis. These scores are referred hereafter as the MEPs.

Repeated measures 2x4x2x2 ANOVAs were carried out on the size of MEPs for the following within-subject factors: posture (left-hand and right-hand forward), the four 150ms time windows[3], object categories (those requiring a precision grip and those requiring power grip) and the muscle type (FDI and ADM). The Greenhouse-Geisser correction was used to correct for violations of sphericity and for pairwise comparisons the Bonferroni correction was used.

4.4 Results

Of the 18 participants whose data were analysed, the data from 3 of them were excluded due to unacceptable signal to noise ratio. The main criterion for data rejection was that ongoing muscle activity prior to stimulus affected the MEP at greater than 15% of TMS trials. Therefore, results were analysed for 15 participants (7 male, 8 female, mean age 26 years 6 months, SD 3 years 11 months).

ANOVA analysis (posture x timing x object category x muscle) of MEP results showed no significance for main effects of posture, object category or muscle type; for each of these main effects the value of $p \geq .289$. All interactions were also non-significant; $p \geq .102$. In fact, unlike previous results from this lab (Makris et al., 2011, 2013) these results showed no interaction effect between object category and muscle. Averaged across posture and time, MEPs on the FDI were not larger following presentation of precision-grip objects (M = -0.227,

[3] More fine-grained analyses of stimulation time were also explored (see Hadar et al., 2016) but yielded no additional information so are omitted.

SE = 0.028) than following power grip objects (M = -0.191, SE = 0.031), and MEPs on the ADM were not significantly larger following presentation of power grip objects (M = -0.244, SE= 0.025) than following precision grip objects (M = -0.256, SE = 0. 022).

There was also no indication that this key interaction was modulated by posture and no evidence that it emerged when considering only the right-hand forward data. Here the precision-grip objects produced very slightly larger MEPs in both muscles (Figure 4.4). For FDI the precision-grip objects M = -0.210, SE = 0.049, power-grip objects M = -0.219, SE = 0.043; for ADM power grip objects M = -0.235, SE = 0.030, precision-grip objects M = -0.214, SE = 0.032.

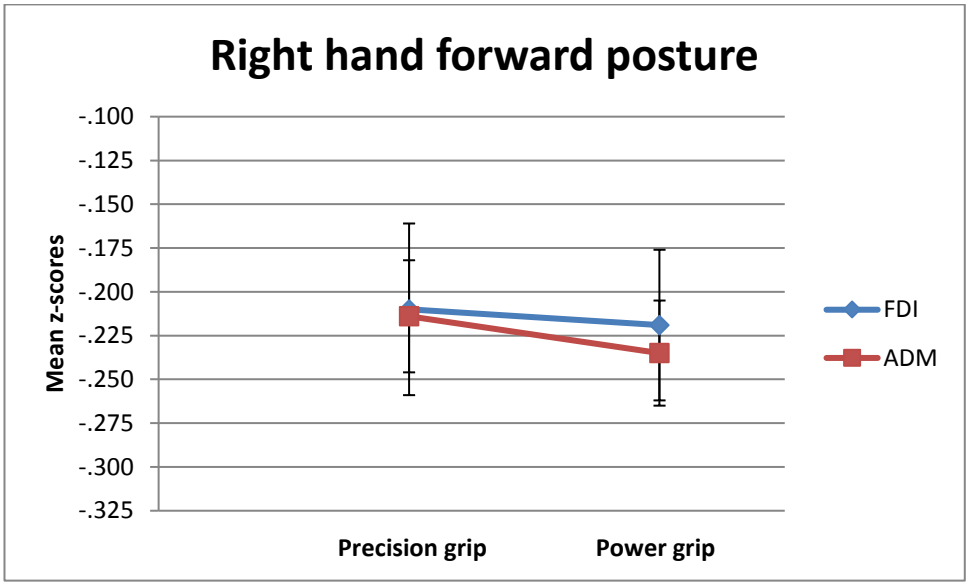


Figure 4.4. Mean MEPs from each muscle for each object type with dominant hand closest to the screen. Error bars denote standard errors.

There was also no indication of a further modulation by time of stimulation, and more specifically, no evidence of the key interaction when considering the posture/time combination with the greatest a priori likelihood of yielding an

affordance effect (based on Makris 2011, 2013). Analysis for the right hand forward posture at the 300ms to 450ms time-window again produced non-significant but slightly larger MEPs for precision grip objects. Here, for FDI the precision grip objects M = -0.318, SE = 0.053, power grip objects M = -0.374, SE = 0.084; for ADM power grip objects M = -0.331, SE = 0.049, precision grip objects M = -0.293, SE = 0.043.

The non-dominant left hand forward posture was not expected to produce a muscle/object interaction. There were no significant differences between object categories for either muscle but the power grip objects produced larger MEPs in both muscles as shown in Figure 4.5.

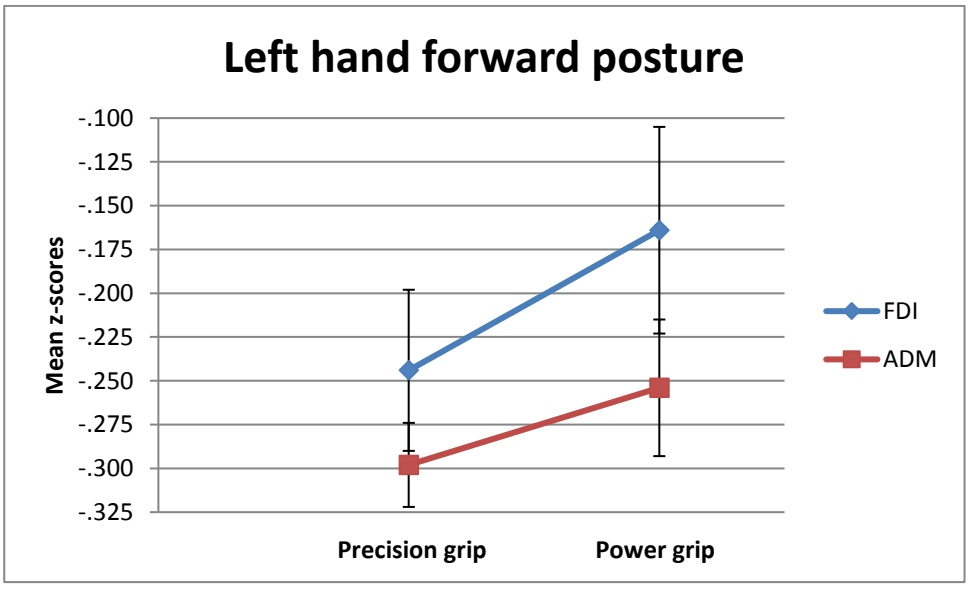


Figure 4.5. Mean MEPs from each muscle for each object type with non-dominant hand closest to the screen. Error bars denote standard errors.

The only significant main effect was revealed for the timing of the TMS pulse delivery, $F(3, 42) = 11.999$; $p < .001$, $\eta p^2 = .462$. Pairwise comparisons showed significant differences between time windows: TW1 with TW3 ($p = .001$); TW1

with TW4 (p = .001); TW2 with TW3 (p = .046); TW2 with TW4 (p = .043). There was not a significant difference between TW1 and TW2 nor was there between TW3 and TW4. In essence, MEPs for the delivery of TMS pulses between 1ms and 300ms were significantly different to the MEPs for the delivery of TMS pulses between 301ms and 600ms with larger MEPs observed in the earlier time windows (Figure 4.6.).

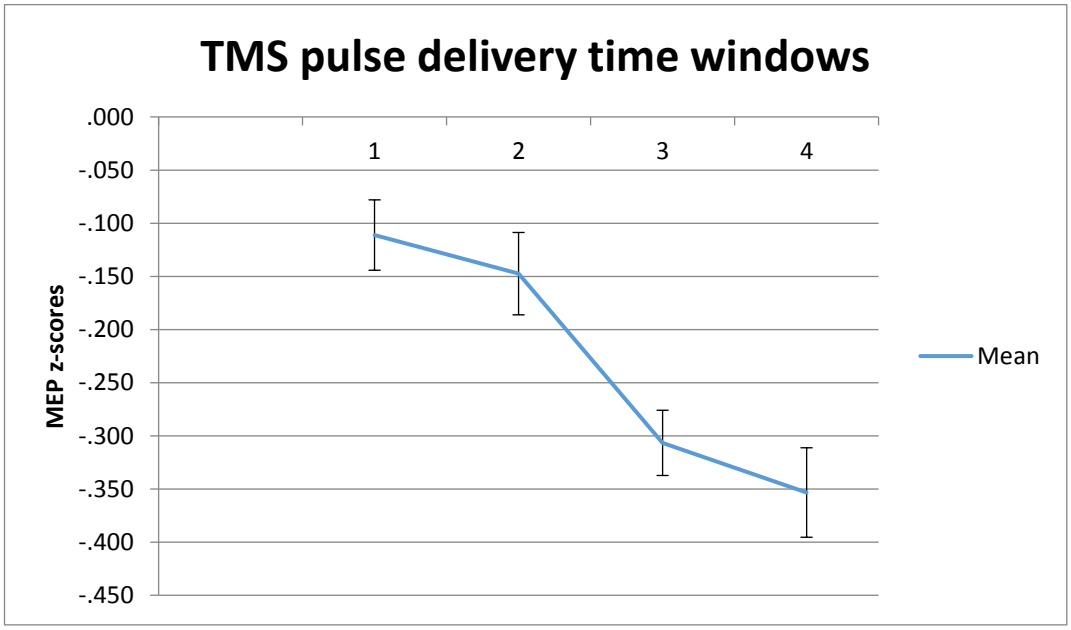


Figure 4.6. MEP z-scores from TMS pulses delivered at the four different time windows (averaged across other experimental factors). Error bars denote standard errors.

4.5 Discussion

In this experiment, an additional manipulation (posture) was added to an established experimental design seeking an interaction between the kind of object being viewed and the size of MEPs evoked in muscles with relevance for different kinds of grip implied by those objects. However, the anticipated modulation of MEP size was not observed. Unfortunately, there is no obvious

reason why affordance and congruency results here did not replicate those of the earlier experiments (Makris et al., 2011 and 2013). In the 2011 study stimuli were two dimensional pictures of objects. In the 2013 study real objects were used, with participants wearing occlusion glasses until a cue when the glasses allowed full vision. Both studies reported that significantly larger MEPs were observed in the FDI muscle when participants viewed thumb and forefinger precision grip objects compared to when they viewed large objects that would require a power grip when TMS was delivered 300ms. The 2013 study also revealed a significant congruency effect for both the FDI and precision (vs. power) grip objects and also for the ADM and power (vs. precision) grip objects when TMS was delivered at 450ms.

The number of trials per condition in this experiment was similar to that reported by Makris et al. (2011) so the current estimates of median MEP size for each participant in each condition should be similarly reliable. Further, to determine whether there were sufficient participants to detect any affordance effects, an effect size was estimated from the studies reported by Makris et al. (2011 and 2013). T-test contrasts between precision-/power-grip objects on the FDI at significant stimulation times were reported as t = 3.20, 3.17 and 2.33. These would imply Cohen's d values of 0.754, 0.879 and 0.646 respectively. Taking the average of these as d = 0.760, a power analysis would suggest that 15 participants would provide power of 78%. Being close to the conventional standard of 80%, this study with useable data from 15 participants should have shown the effect if it were there. (Had there been a trend towards congruency with type of object in either FDI or ADM, analysis for statistical power could have been carried out and then the benefit of a greater number of participants

may have been considered). It is likely that that the effect was greatly reduced or eliminated here by using slightly different methodologies.

4.5.1 Timing

Stimulating at random time points is an unusual approach but, under the assumption that any affordance effect rises and then dissipates with fairly slow dynamics, averaging into four time-windows is similar to targeting discrete time points. Makris et al. (2011 and 2013) showed congruency based affordance effects from MEPs at 300ms and at 450ms. Other researchers have found these earlier. Cardellichio et al. (2011), presenting objects in a computer generated three dimensional space, also achieved affordance effect results when stimulating as early as 50ms after onset.

In the current experiment, the range of stimulation times used should have allowed detection in any of these time windows suggested by previous research. However, no significant MEP differences were revealed for congruency, even in the posture modulation with dominant hand close to the object. Considered in isolation, timing of pulse delivery did produce significant results. Early delivery of TMS pulses, between 1ms and 300ms, produced the largest MEPs whether participants were viewing precision or power grip objects. This is possibly simply a result of general arousal caused by the onset of stimuli.

4.5.2 Stimulus Presentation

A major difference in the current study relative to many previous TMS experiments is that the method called for participants to view the stimuli through a 3D viewer. Although this was a deliberate attempt to show the objects in as realistic manner as possible, it is also possible that the physical properties of the viewer, and/or the quality of the photographs distracted from the actual objects themselves.

A further consideration, as suggested by Righi et al. (2014) is also the aesthetic appearance of the objects. Attractiveness of an implement, as well as its intrinsic affordance-generating characteristics, was explored with speeded responses. Here, a variety of tools were shown while EEG monitored cortical activity. After the stimulus was removed participants were cued to rate the tool for its attractive qualities as well as its action affordance. Results revealed that primarily object function affected early processing (evidenced by ERPs) while attractive qualities as well as function played a role in later processing. Behaviourally, the study concluded that attractiveness and affordance may be additive to produce faster responses or, may cause interference with conflict between an object's aesthetic and functional qualities. Along this line of reasoning, it could be argued that if the aesthetic qualities of a tool or action-related article can increase the affordance effect then perhaps this effect may be enhanced by the aesthetic qualities of any manipulable object. Were the objects in the two earlier experiments from this lab more attractive than the stimuli in the current experiment?

4.5.3 Respond or Passively View

Most affordance-related studies require some form of response to visual stimuli and there are very few TMS studies that require no response from participants. It would appear that passively observing objects while single TMS pulses are delivered does not always elicit congruent responses in muscles related to precision or power grip; nor, indeed, any type affordance effect.

This is not the only time that null effects have been reported for an MEP measure of action-specific affordances. As part of a series of experiments Cattaneo et al. (2005) used a single and paired-pulse paradigm to facilitate I-wave activity and therefore enhance any evoked MEPs. Two physical objects were presented; a handle that would require activation of the FDI, for precision grip, and a disc that would require activation of the ADM, for power grip. Participants wore occlusion spectacles to prevent observation of the experimenter placing objects. Either single pulses were administered or paired-pulses at 130% of the participant's RMT for the first pulse and 90% RMT for the second pulse. After a prior investigation of interstimulus interval (ISI) to determine facilitation and inhibition of activity, the researchers chose to deliver the second pulse at facilitatory ISIs of 1.3ms, 2.5ms, and 4.1ms and at the inhibitory ISIs of 2.1ms and 3.3ms. The single pulse and first of the pair was delivered at 1200ms (±10% jitter) after occlusion glasses were opened. One of the experiments involved participants making the appropriate forefinger and thumb precision grip for the handle or the power grip for the disk immediately after the TMS pulses. Results when single pulses were administered showed no object/muscle interaction. Only paired-pulse results at the 2.5ms facilitatory ISI

showed MEPs from the FDI significantly greater when about to grip the handle and, equally, MEPs from the ADM significantly greater prior to grasping the disk.

In another experiment where participants just passively viewed the objects there were no significant effects from the object identities; no increased MEP from the FDI when viewing the handle and no increased MEP from the ADM when viewing the disk. This was the case for the single pulses and at all of the ISIs for the delivery of paired pulses. Interestingly, even for the 2.5ms ISI the object identity had no significant effect which is a little surprising as this timing did facilitate greater MEPs from appropriate muscles for object identities during the active experiment.

Catteneo et al. (2005) carried out a series of experiments and achieved some successful congruent muscle and object identity results when participants enacted a precision grip or power grip. Hence their non-significant passive viewing results were only a part of the report. Generally, failures are rarely reported so other groups may also have been unsuccessful in their use of TMS during passive object viewing in an attempt to elicit specific muscle responses from FDI, OP or ADM. In fact, Buccino et al. (2009) while achieving significant results for objects with a handle compared to those with a broken handle, did not get significant affordance effects between the OP and FDI muscles. However, it could be argued that both OP and FDI would be activated in a precision grip, making it difficult to detect differences between the muscles.

4.6 Conclusion

It was hoped that results might, to some extent, complement the findings from the EEG experiment (Chapter 3). There were clear expectations relating to position of the dominant hand. Surprisingly, MEPs elicited when the right (dominant) hand was closer to the screen showing an object were not significantly larger than those produced in the left hand forward posture, where participants placed their right hand as far as comfortably possible away from the screen. And, more importantly, this manipulation did not influence the object/muscle congruency effect, which was not apparent in either posture.

Due to experimental differences in the timings of TMS pulse delivery and in methods of stimuli presentation, more research is necessary to ascertain time-courses of affordance effects from the monitoring of MEPs. Perhaps the different forms of stimuli presentation, whether physical objects, 2D or 3D photographs or computer generated objects, should be incorporated into a study where participants are tested viewing each form.

In that vein, as this TMS experiment did not yield expected results, either relating to posture or to congruency effects, a behavioural experiment was developed to try and identify whether responses can be influenced by the manner in which objects are viewed. This experiment is reported in the following chapter.

CHAPTER 5

Investigating precision/power grip affordances via response times

5.1 Introduction

The term affordance, first used by Gibson (1977) describes the functional characteristics of an object in relation to the observer's repertoire of actions. A manipulable object can be said to 'afford' a variety of actions depending on the capabilities of the observer. Affordances have been evidenced by forms of imaging with good spatial properties such as functional magnetic resonance imaging (fMRI) (Grèzes et al., 2003; Rice et al., 2007; Vingerhoets, 2008) and positron emission tomography PET (Grèzes & Decety, 2002). For temporal aspects, TMS (Buccino et al., 2009; Cardellicchio et al., 2011; Franca et al., 2012; Makris et al., 2011, 2013) and EEG are favoured (Goslin et al., 2012; Proverbio 2012; Proverbio et al., 2011; Proverbio et al., 2013; Righi et al., 2014; Vainio et al., 2014). Behavioural experiments have also been employed to detect naturally occurring affordance via speeded responses.

5.1.1 Previous Behavioural Experiments

Stimulus-response compatibility (SRC) measures have driven many behavioural experiments investigating affordances, with forms of compatibility ranging from a simple spatial/directional context for coloured squares (Michaels, 1988) to the orientation of handles in relation to participants' responses (Derbyshire, Ellis, &

Tucker, 2006; Hommel, 2002; Tucker & Ellis, 1998; Tucker & Ellis, 2004) or object stimuli eliciting a specific type of grip response (Makris et al., 2011, 2013). In forced-choice response time (RT) experiments, task-irrelevant aspects of a stimulus have facilitated responses, thus demonstrating SRC effects similar to the Simon effect (Simon, 1969). For example, Tucker and Ellis (1998) used objects with handles. They invited participants to attend to an object's upright or inverted orientation and ***not*** to consider its left-right orientation, responding with a button press by either their left or right index finger depending on whether the object appeared upright or inverted. As expected, response times were significantly faster when objects were upright, but so were responses compatible with orientation (e.g. a right button press to a right-oriented handle), suggesting either abstract left-right coding for orientation or, possibly, potentiation to act caused by intrinsic properties of the object. A second experiment investigated the use of just the index and middle fingers of the right hand for the response. While the upright/inversion results were similar, there was no significant interaction between the horizontal orientation and left-right responses when executed by a single hand. This difference in results between the two experiments, with orientation affecting response only when separate hands were responding, strengthens the argument that objects potentiate actions in the observer.

This seminal work has been confirmed and extended by other behavioural studies (Bub, Masson, & Kumar, 2018; Derbyshire et al., 2006; Makris et al., 2011, 2013; Phillips & Ward, 2002; Symes, Ellis, & Tucker, 2007; Tucker & Ellis, 2001; Vainio, Ellis, Tucker, & Symes, 2007) as well as by EEG (Goslin et al., 2012) and positron emission tomography (PET) (Grèzes & Decety, 2002).

However, an alternative to the automatic affordance-like motor priming theory is the conclusion that this SRC effect is purely spatial, rather than an effect produced by the properties of the object (handle). Cho and Proctor (2010) used variations of a frying pan as stimuli. This implement was chosen for the unambiguous manner in which it is held by the projecting handle. No significant difference for between-hands and within-hand responses were recorded, either for the stimulus with a handle, a disembodied handle or even when just a dotted line was projected towards one side of the screen (in a similar position to where the handle would normally appear).

But Xu, Humphreys, & Heinke, (2015) furthered the suggestion of automatic affordances. In paired-object experiments the implied action of the pair affected participants' responses, even though the objects were task-irrelevant. In two experiments participants viewed line drawings of pairs of objects; one passive, e.g. a bowl and one active, e.g. a spoon, with a target (blue circle or blue triangle) in the centre of the picture (between the two objects). In experiment 1 a further condition was that the co-location of the active object was altered, e.g. on some trials the spoon was directed at an inappropriate angle for use. For experiment 2 on some trials the passive object was co-located incorrectly, e.g. the bowl was upside-down. Participants made a speeded keypress response with the left or right index finger, according to the shape of the central target; circle or triangle.

Task irrelevant responses made by the hand on the same side as the active objects were considered congruent with the affordance of active objects while

those made by the other hand were considered congruent with affordance of the passive objects.

Results for both experiments revealed faster RTs for active compared to passive objects. In experiment 1 RTs were also faster in correct compared to incorrect co-location. Results also revealed that when the active object was correctly positioned, the response congruent with passive objects was slowed compared to when the active object was incorrectly co-located. But in experiment 2 responses congruent with active objects were not significantly affected by whether the passive object was rotated or in the correct position. From the two experiments it would appear that the type of object may covertly affect responses. The authors' main findings further the idea that affordances may be automatically coded, in this instance by pairs of action-related objects.

As well as lateralisation for handles, modulation of affordances has also been attributed to the saliency of an object. Participants have attended to the functional part of the object rather than to its graspable part (Kourtis & Vingerhoets, 2015; Vastano, Finn, & Barnes-Holmes, 2017). Vastano et al. (2017) carried out an Implicit Relational Assessment Procedure (IRAP) (Barnes-Holmes, Barnes-Holmes, Stewart, & Boles, 2010). Participants viewed an object together with a related or unrelated word and made a keypress with their left of right hand for 'true' or 'false'. An example might be the object 'hammer'. If the word was 'garage' the 'true' key would be pressed but if the word was 'kitchen' the 'false' key would be pressed. This was the consistent condition. The experimental design also incorporated an inconsistent condition so that if the hammer appeared with the word 'kitchen', participants would have to respond

‘true’. Compatibility for the responding hand and object handle was also assessed. Faster RTs occurred when the object and word were functionally relevant, whether in consistent or inconsistent trials but there was no significant effect relating hand response with handle. The authors surmised that despite conflicting stimulus-response mappings, functional relevance did, to an extent, modulate affordances.

To circumvent purely spatial explanations of their presumed motor-priming effect, Tucker and Ellis (2001) used an SRC paradigm utilising power or precision grips in response to categories of manmade or natural objects, irrespective of the usual type of grip for such small or large objects. Participants held an unusual manipulanda; a button that could only be activated by a power grip and another activated only by a precision grip. Although object size was task-irrelevant, participants made faster power-grip responses for large objects compared to small objects and faster precision-grip responses for small, compared to large objects.

However these findings were somewhat contradicted by Netelenbos and Gonzalez (2015) who carried out two experiments using both graspable and non-graspable objects in both natural and manmade categories. The first experiment required responses determined by whether or not the image was graspable. RTs were significantly faster for graspable objects. The second experiment required participants to respond to the manmade/natural categories. Unlike the results of Tucker and Ellis (2001), RTs here were not significantly different between the task-irrelevant graspable and non-graspable stimuli. For these results, the authors suggested that affordances are not automatic but that

interaction with an object requires conscious representation. There was a notable difference between the two studies; the 2001 study required a grip response of one type or another and all stimuli could be grasped whereas in the 2015 study, there were specifically non-graspable objects, e.g., car, tree, giraffe.

In fact, several groups have investigated object/grip SRC effects using precision- and power-grip responses. For example, in Makris et al. (2011), participants viewed 2D pictures of task irrelevant precision- and power-grip objects until the stimulus background changed colour, which could occur at different stimulus onset asynchronies (SOAs). Depending on what colour change occurred, participants made a precision or power grip response. Results from correct responses revealed that at the 400ms SOA stimuli of objects requiring a precision grip produced significantly faster precision grip responses than objects that warranted a power grip and vice versa for power grip responses. The effect dissipated at longer SOAs, suggesting a time-limited affordance.

Makris et al. (2013) continued this work by incorporating a monocular/binocular manipulation. Instead of background colour change, this time the imperative stimulus was a high or low pitched tone 500ms after stimulus onset, signalling either a precision or power grip response. Viewing in monocular vision (via liquid-crystal glasses) produced no significant results. But from correct responses in the binocular vision condition, there was a task irrelevant congruency effect for both precision and power grips at 500ms, with the relevant objects producing significantly faster RTs for each type of grip.

The comparison of monocular and binocular vision was motivated by the fact that affordances should be most evident in the natural, i.e. 3D, action environment. Indeed, visual processing differs for 2D and 3D objects from early processing stages. For example visual evoked potentials (VEPs) observed during EEG at occipital electrode sites have been recorded as a negative-going peak at around 100ms after stimulus onset (N1). Such VEPs have also been found to have greater N1 negativity while participants viewed 3D images compared to viewing 2D images (Omoto et al., 2012). In fact, in eleven other studies that Omoto et al. (2012) reviewed, five confirmed increased negative amplitude for the N1 in a 3D condition compared to a 2D condition. The other six studies showed no significant increase or decrease in N1 amplitude for the 3D condition compared to the 2D condition.

As previously observed in this lab (Makris et al., 2011, 2013) objects congruent to the type of grip are expected to produce faster RTs, implying an affordance. Not only should these affordances be greater under more natural (3D) viewing conditions (Castiello & Begliomini, 2008; Melmoth et al., 2009), this should be true particularly when presented in reachable space of the dominant hand but also when the imperative stimulus occurs between 400ms and 500ms of the prime (Makris et al., 2011, 2013).

5.1.2 Current Experiment

The response time (RT) behavioural experiment described here was designed as a consequence of the non-significant congruency results in the TMS

experiment reported in Chapter 4. The EEG experiment (in Chapter 3) revealed that passively viewing manipulable objects from different postures modulated EEG activity. The N2 ERP component was modulated by posture. Left hemispheric activity proved significantly greater in the posture with the dominant right hand closer to objects. Significant differences were seen between the empty desk stimuli and the two object stimuli and, in fact, also between the two types of objects (either requiring a precision grip or a power grip). Consistent with previous EEG and TMS evidence (Buccino et al., 2009; Makris et al., 2011, 2013; Proverbio et al., 2011) it appeared that affordance-related activity occurred within 300ms of stimulus presentation. However, the TMS experiment (Chapter 4) provided none of the congruency effects that had been expected, even with the posture modulation where the dominant hand was closer to the object. The paradigm in the current experiment was modelled on that developed by Makris et al. (2011), the main differences being a posture modulation and that photographs were being presented in 3D (through a stereoscopic viewer) as well as 2D. It was anticipated that 3D pictures of objects would more closely resemble the natural world as in the experiment using physical objects (Makris et al., 2013) compared to viewing two dimensional (2D) images (Makris et al., 2011).

As the congruency affordance effects were not forthcoming in the TMS experiment the decision was made to investigate whether there was a difference between 2D and 3D *images* and which, if either, might elicit a greater affordance effect. However, TMS is a time-consuming technique, and relatively difficult to recruit for, whereas purely behavioural approaches are easier to implement. Therefore a task was incorporated that required either a precision or

power grip response. Manipulanda were employed so that response times could be recorded; either from a button pressed between the forefinger and thumb (precision grip activating the FDI) or by a button pressed when making a whole-hand grasping action (power grip activating the ADM).

5.2. Materials and Methods

5.2.2 Participants

48 participants were recruited through City, University of London Sona System online recruitment and among students within the psychology department (12 males, 36 females; mean age 28.2 years, SD 8.2 years). All had normal or corrected-to-normal vision with no history of any neurological illness. All were right-handed as verified by the Edinburgh Handedness Inventory, adapted from Oldfield (1971). The study was approved by City, University of London Ethics Committee and participants gave written consent. Participants received £8 for their time.

5.2.3 Stimuli and Response Apparatus

The earlier EEG experiment included a ‘no object’ category. As it was planned to observe congruent versus incongruent objects relating to precision grip and power grip, like the TMS experiment, this ‘no object’ category was excluded but there was an increased number of manipulable objects. Similarly to the method reported previously in Chapters 3 and 4, there were initially 40 photographs

chosen as stimulus primes that were rated for type of grip and familiarity. Twenty of these were chosen that were rated either ‘always’ or ‘mostly use this grip’ and either 1/2 or 2/2 for familiarity.

Ten items related to precision grip:

Tweezers, ring, rubber band, rubber, drawing pin, key, highlighter pen, paperclip, roll of adhesive tape, battery

Ten items related to power grip:

Soap dispenser, trowel, mug without a handle (these three depicted in Figure 5.1), knife, anti-perspirant can, wire cutters, screwdriver, drinking glass, hairbrush, pair of pliers.

Figure 5.1.A sample of the power grip objects.

To determine congruent and incongruent responses, the background of the photograph changed colour (this was the test, or imperative, stimulus) to indicate the required response. For example if the background changed to blue, (Figure 5.2) then a finger and thumb precision grip was required. If it changed to yellow, then a power grip was required or vice versa. Background colour change for type of response was counterbalanced across participants and they

were requested to respond with the correct grip for the background colour and not for the type of object. However, irrespective of the colour change, analysis for congruency was also carried out; detection of faster power grip responses for objects affording a power grip compared to objects affording a precision grip and vice versa for precision grip responses.

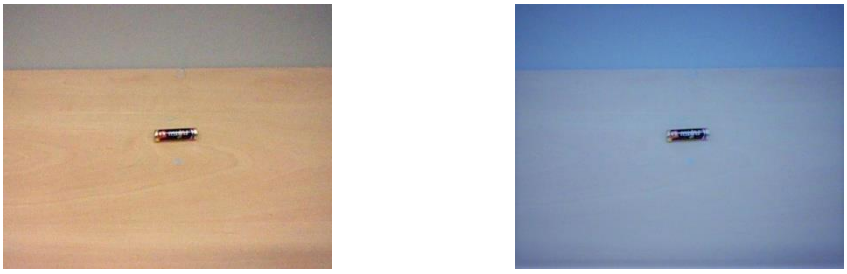


Figure 5.2. Photograph of a precision grip object (battery) as (a) prime stimulus and (b) imperative stimulus.

For the purpose of recording responses, participants held manipulanda in their right (dominant) hand. One response was a simple pinching button held loosely between the thumb and index finger to monitor precision grip when pressed. The second was a button attached to a cylindrical baton held in the palm of the right (dominant) hand. Participants were asked to hold the baton in the palm of their hand and to close their second, ring and little finger around it. It was held loosely until they made a power grip, pressing the button against the palm without using the index finger and thumb (Figure 5.3). They were asked to make a speeded response while also maintaining accuracy.

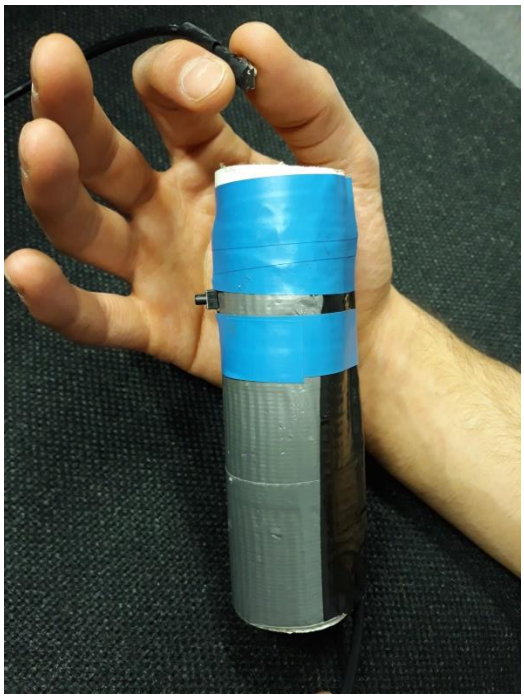


Figure 5.3. The position of the power grip button before participant closed their fingers around it. Precision grip button is being held between the thumb and forefinger.

5.2.4 Design and Procedure

Participants were seated approximately 45cm from a CRT monitor refreshing at 100 Hz. There were two viewing postures. For the right-hand forward posture the right hand rested close to the screen with the body rotated approximately 45° away from the screen towards the left. The head was maintained directly facing the screen. For the left-hand forward posture the left hand rested close to the screen with the body rotated approximately 45° away from the screen towards the right. Again, the head was maintained facing directly towards the screen. In each posture there were two viewing conditions; 2D and 3D. Participants were asked to make an accurate speeded response when the background colour changed to yellow or to blue.

Preceded by a 0.5 second fixation dot, the 2D photographs were presented in the middle of the screen, for a maximum of 10 seconds (including the colour change) or until a physical response was recorded from either manipulanda (Figure 5.4).

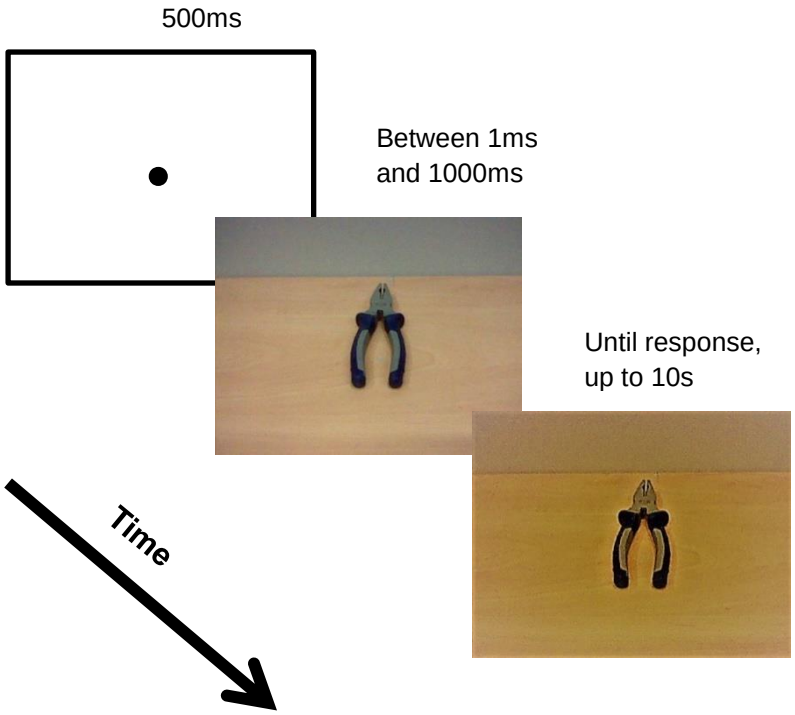


Figure 5.4. Sequence of presentation in typical 2D trial. Here a power-grip object is displayed followed by the yellow imperative stimulus.

For the 3D condition, left-eye and right-eye photographic images were displayed side by side, but presented only to their respective eyes via a mirror stereoscope (Stereo Aids, Albany, Western Australia). Again, they were preceded on the screen by a 0.5 second fixation dot, then presented for a maximum of 10 seconds or until a manipulandum was activated. Initially, participants were allowed time to adjust the viewer so that they observed a single object in three dimensions. For this calibration, two objects, a ball and a

sponge, were presented in alternation and these objects were not used for the experiment.

In general, participants are likely to respond more quickly when an imperative stimulus appears at a later time-point relative to a warning prime. Expectation should be related to the so-called “hazard function”. This is the chance of a stimulus occurring in the next moment if it has not occurred yet. If the SOA is pulled from a uniform distribution, the hazard function increases over time (explaining why one should increasingly expect a stimulus). However, if the SOA is pulled from an exponential distribution, the hazard function is flat, which should eliminate expectancy effects (Luce, 1986). Different SOAs were incorporated to detect when the strongest affordance effect occurred so using the exponential distribution, expectancy (and hopefully mean RT) was equated at different SOAs, giving equal opportunity to observe any congruency effect. Therefore, SOAs were randomly incorporated in this experiment with a (truncated) exponential distribution of SOAs between 1ms and 1000ms.

Each combination of viewing condition and posture was assessed in a separate block. Each block consisted of 280 trials made up of 7 repetitions of each of the 10 objects in both the precision and power-grip categories and for each of the blue and yellow imperative stimuli. There were two rest breaks in each block. The order of the postures and the 2D and 3D viewing conditions was counterbalanced across the participants.

5.2.5 Data Analysis

All data were processed offline using MATLAB (version R2015b), Microsoft Excel (2013 edition) and IBM SPSS statistics 22. Errors were judged to occur when the first response that was logged (indicating a precision or power grip) was incorrect based on the background colour change for that trial. All participants showed an error rate of less than 10%, thus no participant was excluded from the analysis on this basis. For the purposes of this analysis the prime to imperative target (background colour changes) SOAs that occurred randomly between 1ms and 1000ms were separated into two SOAs. Short SOA was less than the individual participant's median SOA and long SOA was greater than their median SOA as indicated in Figure 5.5.

Mean response times (RTs) were calculated using only correct trials for each participant in each condition. These were submitted to a 2x2x2x2x2 repeated-measures analyses of variance (ANOVA); within-subject factors being posture, dimension (2D/3D), SOA (short and long), type of response (power/precision grip) and congruency for the type of object viewed (objects eliciting either a power or precision grip, re-categorised as being congruent/incongruent with the response). Bonferroni corrections were applied for paired comparisons.

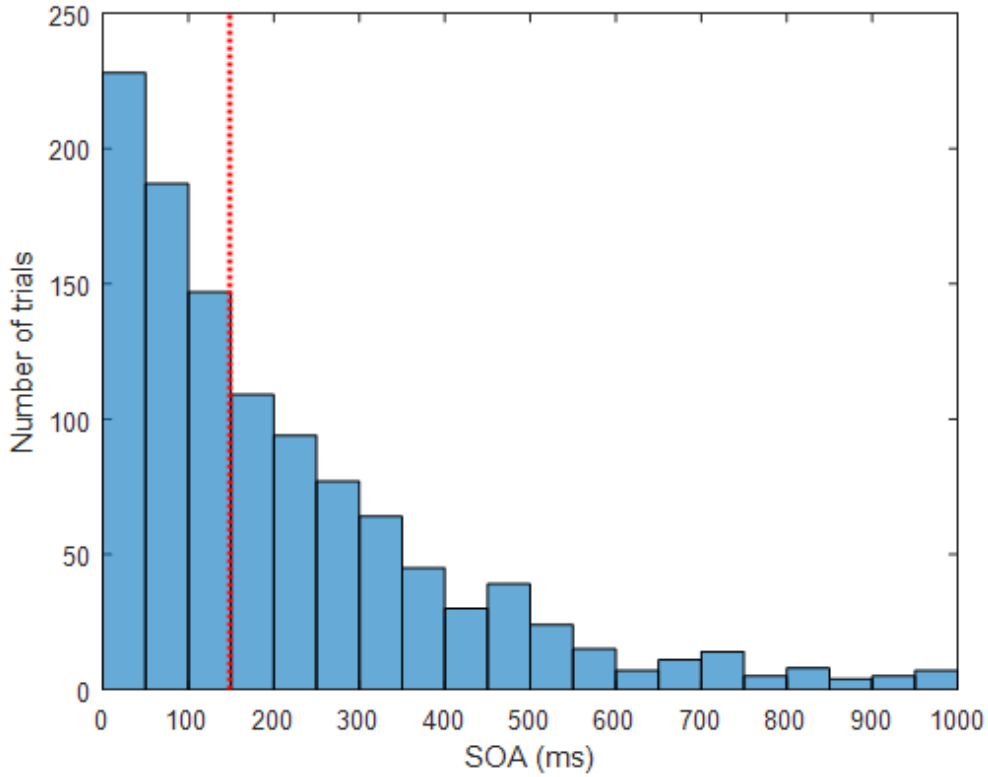


Figure 5.5. An example distribution of SOAs from one subject, with red line indicating median SOA.

5.3 Results

In the 2x2x2x2x2 ANOVA (posture x dimension x SOA x response x congruency) the highest-order significant interaction was between SOA, response and congruency, $F(1, 47) = 14.440$; $p < .001$, $\eta p^2 = .235$. As an a priori question related to congruency, this interaction warranted further exploration. The interaction is depicted in Figure 5.6. Responses were considered congruent when precision-grip responses were made to pinchable objects and power-grip responses were made to graspable objects; otherwise, they were considered incongruent. Congruency effects always appeared small, with more pronounced differences between different SOAs and modes of response.

To unpack this interaction, with a focus on any modulation of the theoretically critical congruency effect by other experimental factors, data were collapsed across posture and dimension (as depicted in Figure 5.6) and a 2x2 response by congruency ANOVA was carried out at each level of SOA.

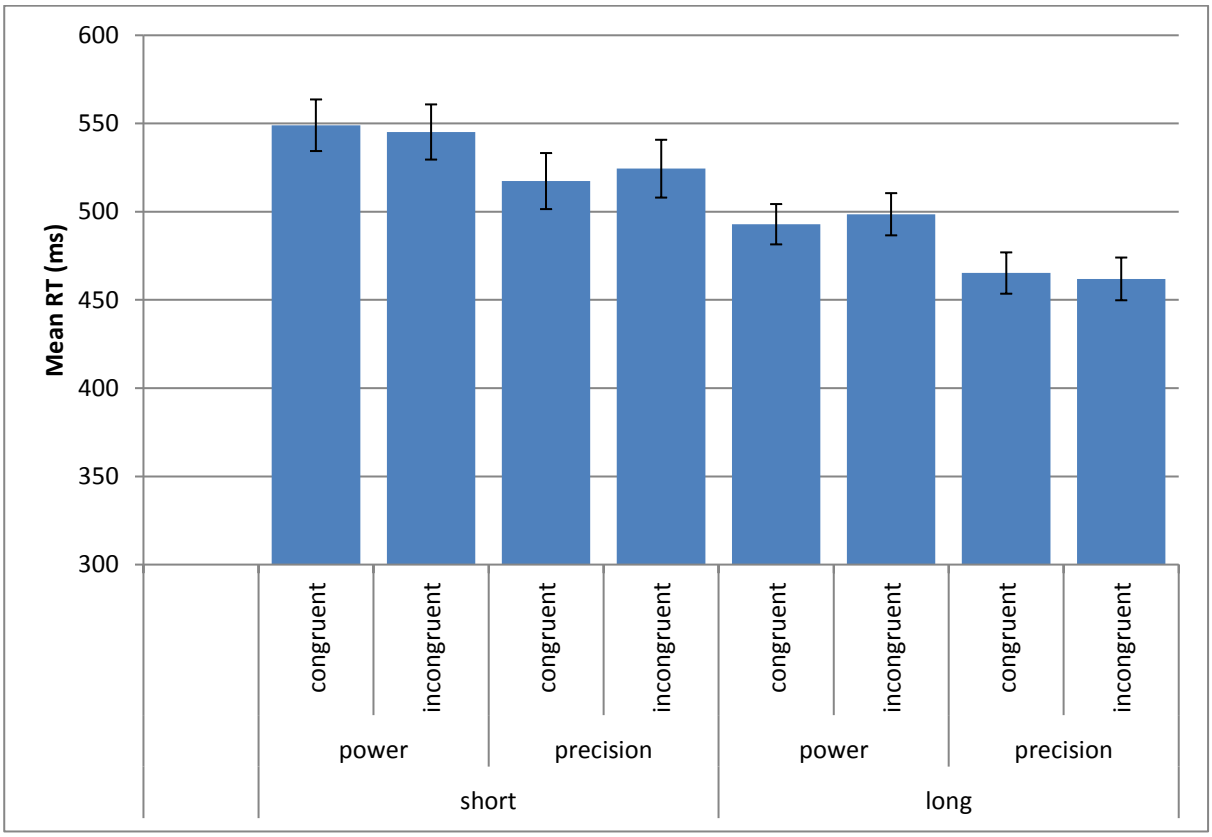


Figure 5.6. Power and Precision Grip Congruency at Short and Long SOAs**.** Response times with error bars showing standard error. Overall, there were faster responses at long SOA and for precision grip responses.

For both short and long SOAs there was a significant interaction between response and congruency (for short SOA, $F(1, 47) = 5.070$; $p = .029$, $\eta p^2 = .09$ and for long SOA, $F(1, 47) = 7.337$; $p = .009$, $\eta p^2 = .135$). Pairwise follow-ups comparing congruency for both type of grip were all non-significant. For power grip at short SOA $p = .280$ (congruent *M = 549, SD = 116*; incongruent *M = 545,*

SD = 125). For precision grip at short SOA p = .053 (congruent *M = 517, SD = 124;* incongruent *M = 524, SD = 126*). For power grip at long SOA p = .065 (congruent *M = 493, SD = 89*; incongruent *M = 499, SD = 92*). For precision grip at long SOA p = .203 (congruent *M = 465, SD = 92*; incongruent *M = 462, SD = 92*). Responses for precision grip were all faster than those for power grip.

The congruency effect is non-significant in all cases, but the size/direction of the effect changes. The significant three-way interaction can be explained by the way the congruency effect is changing across conditions (the anticipated trend for short SOA precision responses and long SOA power responses, but the opposite trend in the remaining two cases) but the effect remains non-significant in all cases. Hence the result is not compatible with a congruency effect that emerges in some cells of the design and not others (particularly as the way the effect changes across responses and times is hard to explain – if affordances emerged at a particular time, this should be observed consistently for both responses, but in fact they are doing opposite things at opposite times).

The interaction was also considered from other less theoretically derived points of view (e.g. as modulation of the effect of response, or as a modulation of the effect of time, by the remaining factors) but in all cases, the main effect (or absence thereof) was ultimately present in every cell of the design, just to very slightly different extents.

The second highest-order interaction was a significant interaction between dimension and SOA, $F(1, 47) = 5.830$; $p = .020$, $\eta p^2 = .110$. The interaction is

illustrated in Figure 5.7. In pairwise comparisons, following averaging over the other three factors, it was only for the short SOA conditions that there was a significant difference between the dimensions (Figure 5.7), with faster responses for 2D primes compared to 3D primes (p = .010).

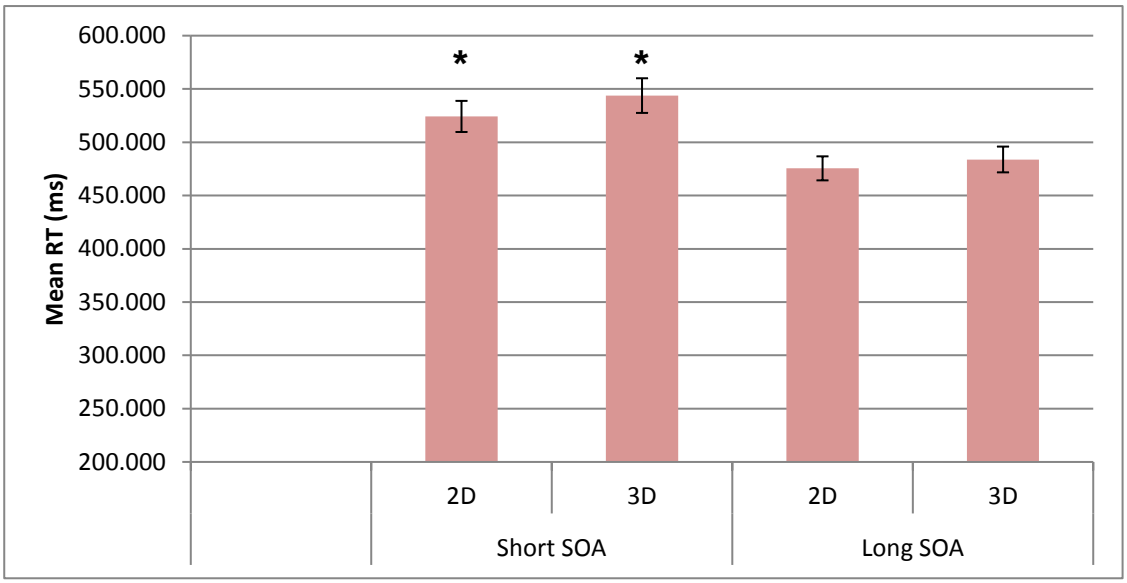


Figure 5.7. 2D and 3D at Separate SOAs. Response times for the different dimensions at different SOAs. Responses in the 2D condition were significantly faster than responses in the 3D condition at the short SOA.

There was no significant main effect of posture (right hand forward *M = 506, SD = 109*; left hand forward *M = 507, SD = 116*), nor any significant main effect of congruency (congruent *M = 506, SD = 110*; incongruent *M = 508, SD = 114*). There were significant main effects of dimension, $F(1, 47) = 5.564$; $p < .023$, $\eta p^2 = .106$ where 2D responses were faster than 3D (2D *M = 500, SD = 207*; 3D *M = 514, SD = 117*) and also of SOA, $F(1, 47) = 65.675$; $p < .001$, $\eta p^2 = .583$ with long SOA conditions having faster response times (short SOA *M = 534, SD = 124*; long SOA *M = 480, SD = 92*). Finally, response types differed,

$F(1, 47) = 26.298$; $p < .001$, $\eta p^2 = .359$, with precision grip responses faster than power grips (precision *M = 492, SD = 113*; power *M = 521, SD = 110*).

5.4 Further Analysis

In the absence of compelling congruency effects, or interpretable interactions involving congruency, a post-hoc analysis was employed, and adopted the following logic. While it would clearly be cherry picking to select subsets of trials by searching for congruency effects, and then claim this as evidence of an affordance (i.e. based on congruency), it might be acceptable to select subsets of trials on the basis of congruency if the presence of an affordance was then tested using a different criterion. The design offered such an independent criterion, in the presence of an *enhanced* congruency effect for the right-hand forwards posture.

Investigating the possibility that some objects with lesser intrinsic manipulable properties may have reduced any congruency/affordance effects, i.e. to see if any particular objects produced better data, 5 objects were selected from each of the precision-grip and power-grip categories. The soap dispenser, knife, glass, mug and brush for power grip and the drawing pin, paperclip, tweezers, ring and button for precision grip were the objects with the greatest difference between congruent and incongruent response times. Data relating to these objects were then analysed to get median RTs for each participant. Differences between congruent and incongruent responses were calculated for each participant and then a 2x2x2 ANOVA was carried out in respect of posture, dimension and type of power/precision grip response. However, it revealed no

significant differences in congruency effects for these objects at all. In fact, for all interactions and main effects $p > .100$.

The final consideration was to analyse whether congruency effects were greatest at a particular SOA, i.e. time from the prime to the imperative stimulus, when the background changed colour. Again using collective data, comparisons were made between congruent and incongruent responses in 20ms time bins. The largest RT enhancement of congruent compared to incongruent responses was specifically when the imperative stimulus occurred between 300ms and 340ms after the prime.

Reviewing individual data sets, for 3 participants there were insufficient trials to calculate congruency effects in this window. From the congruent results of 45 data sets with the SOA between 300ms and 340ms, a 2x2x2 ANOVA for posture, dimension and type of grip response produced no significant main effects. However, there was a significant interaction between posture and dimension $F(1, 44) = 5.66$; $p = .022$; $\eta p^2 = .114$. Carrying out pairwise comparisons revealed a significant difference between postures in 2D conditions ($p = .009$). However, this was not in the direction required to provide evidence of an affordance, with the left-hand forward posture producing larger congruency effects.

5.5 Discussion

In this experiment a set of photographs of objects were presented in separate blocks in 2D and in 3D and with participants seated in different postures, either with their right (dominant) hand or their left hand close to the monitor. When the background of the photograph changed colour, participants were to press one of two buttons; either between the forefinger and thumb in a precision grip or against the palm in a power grip. The type of response depended on the colour change, either to blue or to yellow, irrespective of whether the object afforded a power or precision grip.

5.5.1 Congruency Effects

An effect of congruency between prime objects and the actions they afford has appeared in SRC studies in general (e.g. Bub et al., 2018; Tucker and Ellis, 1998, 2001, 2004) and been found specifically in this lab by Makris et al. (2011, 2013). It is therefore puzzling that no such effect emerged here. Not only was there no overall congruency effect, there was no evidence that such an effect emerged specifically, or to a greater extent, in conditions that should increase the behavioural relevance of the primes, e.g. when posture promoted interacting with these objects. Makris et al (2011) carried out a similar reaction-time experiment where participants observed 2D pictures. Their results did show significantly faster RTs for objects congruent to the type of grip response; for both precision and power grip. This interaction was observed at 400ms but not at the later SOAs of 800ms and 1200ms. RTs in the current study were faster for congruent compared to incongruent responses but not significantly. This is slightly surprising as it had been hoped to replicate the earlier study from

this laboratory. Carrying out a power analysis using the precision-grip congruency effect size from Makris et al (2011) of Cohen's d~0.660, and the sample size here, N = 48 (for a paired t test, alpha = 0.05, two tailed), suggests a power of 0.994. Therefore this congruency effect should have been detected. Possible explanations are that perhaps the objects chosen were less able to produce an affordance effect than those used previously, or that the photographs were not of a sufficient resolution to best portray the properties of the objects. It is also possible that the unusual continuous distribution of SOAs rather than discrete values, e.g. 300ms, 350ms, 400ms, affected the results.

The final part of the analysis showed some significant congruency effects when background colour changed at an SOA of between 300ms and 340ms. This time window is similar to those in earlier experiments which produced more comprehensive results (Makris et al., 2011). In that 2011 RT study, as mentioned above, congruency was observed for type of response (power/precision grip) at 400ms SOA and in the follow-on TMS study, larger MEPs for congruent objects and type of response was observed particularly at 300ms. The current study with SOA between 300ms and 340ms revealed a significant interaction for the modulation of the congruency effect, between posture and dimension. However, again, it is surprising that the larger congruency effects were found for the non-dominant left hand forward condition. This is not suggestive of an effect driven by affordances.

5.5.2 Postural Effects

It would seem logical for right-handed participants to react faster with their dominant hand closer to the objects. For example, if there was a very general affordance effect this should be the case for both precision and power grip responses, regardless of the actual object presented. However, the main ANOVA revealed no significant differences between the right and left hand forward postures. Many previous studies have explored lateral effects with stimuli being presented with handles either to the left or to the right (e.g. Bub et al., 2018; Cho & Proctor 2010; Grèzes & Decety, 2001; Tucker & Ellis, 1998). Although no such laterality was present in the stimuli used here, the blockwise manipulation of posture could be considered to similarly make the right hand more or less appropriate for interacting with the object.

While there is still debate regarding spatial compared to affordance effects (e.g. Cho & Proctor, 2010; Proctor & Miles, 2014), evidence from PET scans (Grèzes & Decety, 2001) as well as other behavioural studies (e.g. Bub et al., 2018; Makris et al., 2011) have extended the results of Tucker and Ellis (1998). Their results showed that left and right hand responses were faster for object handles directed towards the left or right, but no such effect was found for responses to the same stimuli made with different fingers of just one hand.

Speculating on the lack of anticipated dominant hand posture modulation result, on the basis that only the right hand was used, and there was never any expectation by participants to respond with the left hand, some postural effects may have been negated. Alternatively perhaps posture results were unduly

influenced simply because those who are right-handed and who use a computer mouse rather than the touchpad, generally use it to the right side of the keyboard (Delisle, Imbeau, Santos, Plamondon, & Montpetit, 2004; Lin, Young, & Dennerlein, 2015; Peters & Ivanoff, 1999). In such cases, although the body is not actually rotated to the right, the right hand is actively occupied (as it was with the manipulanda) several centimetres away from the screen. The left hand is free to carry out keyboard tasks closer to the screen. This has a similarity to the left-hand forward posture. Participants were not questioned about whether they generally used a mouse or a touchpad on laptops or netbooks as this had not been considered until the experimental data had been analysed. However, the unexpected fact still remains that the fastest congruent responses during the most reliable time-window (300ms to 340ms SOA) occurred when participants were seated in the posture with their left hand closer to the screen. Perhaps a stronger approach to reveal the relevance of posture with motor priming might have been to repeat the whole procedure with manipulanda in the non-dominant left hand as an additional factor. Presumably, overall responses would be slower for the left hand than the dominant right hand but it would be interesting to observe whether there were any clear postural effects under such conditions.

5.5.3 Dimensions

The question arises whether 2D images offer better motoric priming than 3D images. 2D pictures are known to evoke ‘dual awareness’ (Gibson, 1971; Yang, Dixon, & Proffitt, 1999). Looking at a 2D scene the viewer is aware that it is a surface in two dimensions and at the same time aware that items depicted in

that surface are actually three dimensional. The image can be perceived as 3D by various static cues; for example shadows, edge effects, and the convexity assumption (Todorović, 2014; Watson & Enns, 2012). Shadows offer depth cues and allow us to infer the direction of light, and most surfaces that we encounter are convex rather than concave (consider the hollow mask illusion), equally assisting depth perception.

Overall, RT was quicker in 2D compared to 3D conditions. This effect was more evident at shorter SOAs. Could it be in the 3D case that the binocular fusion process took up more visual resources, acting as a distraction and slowing RTs, or simply that looking through the viewer distracted from the task? Perhaps a method to make a better comparison between 2D and 3D would have been to have participants view the 2D picture through the same viewer. It would be possible to manipulate the viewer so that just one, 2D picture can be observed.

5.5.4 Stimulus Onset Asynchronies (SOAs)

Most behavioural studies employ discrete imperative SOAs (e.g. Bub et al., 2018; Derbyshire et al., 2006; Symes et al., 2007) but here in an attempt to detect the time that the strongest affordance effect occurred, and control expectancy effects, different SOAs from 1ms to 1000ms were randomly incorporated. The long SOA conditions would have contained trials at SOAs where congruency effects have previously been observed at around 400ms (Makris et al., 2011) but also drew from a wider range (150ms to 1000ms), perhaps tempering the effect. The exponential distribution didn't entirely eliminate RT differences as planned, but perhaps even if expectancy was

controlled, the very rapid onset of the imperative stimulus at short SOAs in combination with the large, complex prime, was distracting. Decreasing RTs are quite often seen in the 0-250ms SOA range even with exponential distribution (Luce, 1986).

5.6 Conclusion

Results from the EEG experiment, suggesting the presence of affordances (Chapter 3) could not be extended in the TMS experiment (Chapter 4). The current RT experiment was devised mainly to determine whether the 3D stimuli presented in the TMS experiment were in any way instrumental in preventing congruent muscle/object effects that had previously been observed in this laboratory (e.g. Makris et al., 2011). Results revealed no significant effects relating to which hand was closer to the screen, or to congruency between object and response grip, regardless of viewing condition. Hence the 3D nature of the stimuli was probably not the problem in chapter 4 (as even with 2D stimuli, behavioural effects failed to emerge here). There was a significant overall effect between dimensions, with 2D primes producing the faster responses, particularly at short SOAs. There was also a significant effect for the time that the background colour changed relative to the prime (SOA). With the SOAs separated into short and long bins, the long SOA produced faster responses.

The lack of significant congruency effects was the most surprising result. However, due to the success of the original EEG study with young adults, a similar EEG investigation with stroke survivors and age-matched controls was planned, for which some alternative objects were considered. The report for this experiment follows.

Chapter 6

Investigating affordance activity in stroke survivors:

An EEG experiment

6.1 Introduction

Infarct by stroke and impaired activity of surrounding cells may result in loss of motor function. The part of the body affected and extent of motor deficits may be exacerbated due to diaschisis; regions distal from the lesion becoming compromised due to changes in metabolism, blood flow and neurotransmitter regulation. However, the human brain, particularly the cortex, has an ability to reorganize the structure and function of neural systems. This neuroplasticity is evident in all forms of learning where neuronal roles adapt to demand, e.g. learning a musical instrument. It has long been associated with stroke recovery and rehabilitation (Pekna, Pekny, & Nilsson, 2012).

Lesions caused by left hemisphere stroke can lead to the motor planning disorder, apraxia (Dovern, Fink, & Weiss, 2012). Different categories of apraxia affect different aspects of motor planning and tool use but in all cases patients typically have lost the ability to carry out purposeful movements of the hand or arm, despite having the physical ability and conscious desire to do so (Cantagallo, Maini, & Rumiati, 2012; Dovern et al., 2012). Neuroplasticity is an essential factor in the recovery of upper limb function, whether or not reduced mobility is due specifically to apraxia (Buxbaum et al., 2008).

As well as gesture recognition and imitation, and pantomiming the use of tools, it is common to offer tools and other manipulable objects as visual cues to aid recovery in therapeutic settings (Dovern et al., 2012; Pazzaglia, Smania, Corato, & Aglioti, 2008; Wheaton et al., 2008). When presenting manipulable objects, interventions utilising naturally occurring "affordances" may assist neuroplasticity (Kühn, Werner, Lindenberger, & Verrel, 2014). The expression "affordance" was first introduced by J.J. Gibson (1977, 1979) who suggested that just by viewing an object we perceive one or more ways to interact with it. However, the length of time during which such a visual cue has its optimum rehabilitative value has, thus far, received little attention. As outlined below, evidence from neurologically healthy individuals may be informative in this regard, but requires generalising to stroke populations.

The term affordance is now commonly used to link potentiation of motor planning with the intrinsic properties of an object. Such automatic motor priming occurs when an object is viewed, whether or not there is any conscious intention to interact with it. This has prompted many studies investigating the existence of affordances in both human and non-human primates (e. g. Grèzes et al., 2003; Murata et al., 1997; Rice et al., 2007; Tucker and Ellis, 1998, 2001; Valyear et al., 2007).

Many findings suggest that affordances exist in healthy humans. However, recently the time course with which they develop and dissipate has generated particular interest. A number of transcranial magnetic stimulation (TMS) experiments have attempted to address this temporal aspect of affordances (Buccino et al., 2009; Cardellicchio et al., 2011; Franca et al., 2012; Makris et

al., 2011, 2013). For example, single-pulse stimulation over left motor cortex facilitated larger motor evoked potentials (MEPs) at around 200ms after onset of stimuli when objects were presented with handles orientated towards the dominant right hand (Buccino et al., 2009). Similarly, MEPs were modulated for congruent hand muscles while participants viewed objects affording either a power or precision grip (Makris et al., 2011). Here, electromyography (EMG) recordings from the first dorsal interosseous (FDI), required when making a precision grip, were significantly greater for observation of precision-grip affording objects compared to larger, power-grip objects, and vice versa for the abductor digiti minimi (ADM), a muscle involved in power gripping. Greatest facilitation occurred at around 300ms, but, interestingly, the affordance effect died away shortly thereafter.

Electroencephalographic (EEG) studies have also sought to measure the timing of affordances. Some have compared responses to pictures of tools with non-tools (Proverbio 2012; Proverbio et al., 2011) or pictures of objects compared to no object (Rowe, Haenschel, Kosilo, & Yarrow, 2017). Proverbio et al. (2011) found significantly greater anterior left hemispheric negativity for the N2 component of the event-related potential (ERP) while viewing tools (including some objects being associated with specific motor acts, such as a bicycle, stairs and a keyboard) compared to non-tools, i.e. objects not strictly associated with a motor act, e.g., a television, a carpet and a piece of pottery. The N2 is the second negative component after stimulus onset and has been associated with motor facilitation (Allami et al., 2014). Using 128 electrodes, Proverbio et al. (2011) computed the N2 from electrode sites AF3, AF4, AFP3h and AFP4h, in a time window was from 210ms to 270ms after stimulus onset. A standardized

weighted low-resolution electromagnetic tomography (swLORETA) inverse solution was computed to understand the source of this increased activity for tools. In response to tools it revealed more left than right hemispheric pre-motor activity (Brodmann Area 6), as well as unilateral (left hemisphere) activation of the somatosensory cortex (Brodmann Area 3). The swLORETA computation showed that these areas were not involved in response to other (non-tool) objects.

The defining feature of an affordance is that it represents priming of the *motor* system (regardless of the ultimate requirement to act or not). Despite the existence of techniques like swLORETA, outlined above, the low spatial resolution of EEG makes this kind of attribution relatively difficult. However, as reported in Chapter 3 greater left hemispheric N2 activity was found when a manipulable object was observed compared to no object (just an empty desk) but particularly when the dominant, right, hand was positioned closer to the object.

These results suggest that the motoric N2, which is modulated by the presence/absence and functional significance of objects, may provide a sensitive measure regarding the presence of motor priming, i.e. an affordance. However, there are (at least) two outstanding questions which need to be addressed in order to move from the evidence showing affordances in healthy young participants towards a basic research justification for testing the potential of affordances to improve rehabilitative outcomes (e.g. a clinical trial). Firstly, we need to know whether motor priming still occurs in (undamaged) regions of the brains of stroke survivors. Secondly, given that affordance-related activation

appears to be transient, we need to know the best rate at which to re-introduce objects in order to generate maximum motor priming within a time-limited therapeutic session.

In summary:

1) Can ERP evidence of affordances be observed in chronic stage stroke survivors?

2) If so, does the time-course of affordances, and/or their modulation by the rate of object presentation, differ relative to that found in age-matched control volunteers?

6.2 Materials and Methods

6.2.1 Participants

Original plans were for acute stage stroke patients to participate. However, it was prudent to investigate with young healthy participants to determine whether affordance activity could be identified from this paradigm prior to engaging with a patient population. Consequently, after achieving successful results, rather than delay the study to seek NHS ethical approval to recruit patients, a decision was taken to investigate at the chronic stage after stroke. Diagnosis of apraxia was originally part of the recruitment criteria but no such volunteers were forthcoming. Therefore 10 stroke survivors (7 male, 3 female; mean age 65 years, SD 9 years) were recruited from an advertisement placed online through the Different Strokes charity and via stroke clubs affiliated to The Stroke

Association. Eight of these participants had left hemisphere lesion and two had right hemisphere lesion. Mean number of years post-stroke was 6.5 years (range 2 – 17 years). All participants had upper limb deficits to varying degrees, but none specifically had a diagnosis of apraxia. Most were able to provide only limited information regarding site of lesion and type of stroke (see Table 6.1).

Through local University of the Third Age groups 15 similarly aged neurologically healthy control volunteers were also recruited (4 male, 11 female; mean age 72 years, SD 5 years). Participants from both groups had normal or corrected-to-normal vision. All healthy control participants were right-handed and all stroke survivors had been right-handed prior to stroke, as verified by the Edinburgh Handedness Inventory, adapted from Oldfield (1971). Laterality Indices (LI) are shown in Table 6.2. For stroke survivors these are indicated prior to and post stroke. All participants achieved ≥ 27 out of a total of 30 for a Mini-Mental State Examination, adapted from (Folstein, Folstein, & McHugh, 1975) (Appendix C) and all attempted a nine-hole peg test (NHPT). Some stroke survivors were unable to complete the NHPT with their affected hand (see Table 6.2). The study was approved by City, University of London Ethics Committee and participants gave written consent.

Table 6.1. Stroke survivor participant ages, number of years post stroke, area of lesion and residual deficits.

Participant	Age	Years post-stroke	Area of lesion	Residual neurological deficits
FS01	60	2	Left lenticulostriate ischemic stroke	Incoordination of right upper limb, and weakness in right lower and upper limbs
FS02	47	4	Left hemisphere	Aphasia, loss of function of right upper limb and weakness in right lower and upper limbs
FS03	67	11	Left hemisphere	Aphasia, loss of function of right upper limb and weakness in right lower and upper limbs
MS01	74	5	Left middle cerebral artery infarct, left internal carotid artery stenosis	Slightly reduced function in right upper limb.
MS02	72	17	Right hemisphere	Reduced flexion in left hand. Reduced flexion and extension of left elbow.
MS03	64	3	Right carotid artery blocked (left partially blocked)	Left lower limb weakness, non-functioning left upper limb
MS04	68	6	Left middle cerebral artery infarct	Aphasia, severely reduced hand function, weakness in right upper limb
MS05	71	4	Left basal ganglia haemorrhagic stroke	Right sided weakness, Returning activity to previously non-functioning right upper limb
MS06	75	3	Left partial anterior circulation stroke (PACS) CT scan showed a wedge-shaped infarct in left posterior frontal lobe	Aphasia, some loss of function and weakness in right upper limb
MS07	52	10	Left hemisphere	Aphasia, non-functioning right upper limb

Table 6.2. Participant ages, mini mental state exam (SMMSE) scores, handedness LI and nine hole peg test timings (N/C = not completed) (FC = female control volunteer, MC = male control volunteer, FS = female stroke survivor, MS = male stroke survivor)

Participant	Age	SMMSE score (/30)	LI for hand dominance	NHPT right hand (s)	NHPT left hand (s)
FC01	68	30	100	22	29
FC02	68	30	100	20	23
FC03	73	30	100	27	21
FC04	79	28	76	25	30
FC05	77	30	72	32	22
FC06	66	30	100	19	21
FC07	75	29	100	26	30
FC08	65	30	82	22	22
FC09	79	30	100	26	25
FC10	69	29	100	24	27
FC11	80	29	100	24	22
MC01	74	30	50	19	18
MC02	68	30	64	24	20
MC03	69	30	100	24	23
MC04	71	30	29	19	18
FS01	60	26	100 prior 56 post-stroke	50	24
FS02	47	29	100 prior -100 post-stroke	N/C	19
FS03	67	28	100 prior -100 post-stroke	N/C	27
MS01	74	30	92 prior 43 post-stroke	56	25
MS02	72	29	100 prior and post-stroke	33	N/C
MS03	64	30	100 prior and post-stroke	29	N/C
MS04	68	29	100 prior -100 post-stroke	N/C	27
MS05	71	28	100 prior -100 post-stroke	N/C	28
MS06	75	29	76 prior -100 post-stroke	N/C	25
MS07	52	27	100 prior -100 post-stroke	N/C	30

6.2.2 Stimuli

Initially, 3D photographs were taken of 40 objects (full details of object criteria and photographic methods in Chapter 3). Independent assessors rated these photographs on whether they would use a forefinger and thumb precision grip or whole hand power grip to hold the objects and also on familiarity of the objects. Feedback from participants in the earlier study (Chapter 3) was also taken into account when a set of pictures was chosen which contained good exemplars of objects affording either a precision or power grip. These stimuli were used to construct three stimulus categories. The first category contained only a single stimulus (an empty desk) while the other two showed objects located on the desk. Object categories consisted of one picture of each of three objects, which would normally be held in either a precision grip (a wax crayon, a pencil sharpener and a wrapped sweet) or a power grip (a hairbrush, a trowel and a box).

6.2.3 Design and Procedure

Similarly to the earlier EEG experiment, participants were seated in an electrically shielded room, in front of a desk-mounted stereoscope, approximately 45cm from a gamma-corrected CRT monitor refreshing at 109 Hz. Left-eye and right-eye images were displayed side by side, but presented only to their respective eyes via the mirror stereoscope. Initially, participants were allowed time to adjust the viewer so that they observed a single object in three dimensions. For this calibration, two objects, a ball and a sponge, were

presented in alternation. These two objects became targets for a subsequent vigilance task.

For the main experiment, there were two stimulus presentation rates. At the 0.5 Hz rate (R1) on each trial, two fixation dots were shown on screen for 1000ms (to maintain stereo fusion in the interval between pictures) followed by a colour photograph, also for 1000ms. At the 1 Hz rate (R2) the fixation dots and colour photograph each appeared for only 500ms. The task was to passively view the pictures through a stereoscopic viewer, except that participants had to report the two target items (ball and sponge) whenever they appeared (with these trials excluded from the subsequent data analysis).

There were object and no-object trials, 180 of each in a block. The object trials were further divided into precision-grip and power-grip objects. Because the number of trials proved to be sufficient to pick out meaningful differences between object categories, the analysis is presented based on all three conditions. For the vigilance task, the ball and sponge pictures were included in an additional 16 trials. Trials in each object category and those of the vigilance task were presented in a randomised order.

As in the previous EEG experiment, there were two viewing postures. For the right-hand forward posture the right hand rested close to the screen with the body rotated approximately 45° away from the screen towards the left. The head was maintained directly facing the screen. For the left-hand forward posture the left hand rested close to the screen with the body rotated approximately 45° away from the screen towards the right. Again, the head was

maintained facing directly towards the screen. Each participant completed four blocks, with the procedure alternated across four possible orderings (of posture nested within presentation rate). For the 0.5 Hz rate (R1), in each posture a block lasted approximately 13 minutes, while at 1 Hz (R2), in each posture a block lasted approximately 6½ minutes. In both timings, participants were offered a short break after 126 and 252 trials.

6.2.4 EEG Measurement and Analysis

A 64-channel electrode cap was fitted to the participant's head with the ground electrode at position AFZ and the reference electrode at position FCZ. An additional vertical electro-oculogram electrode was placed below the left eye. EEG was recorded at a sampling rate of 1000 Hz. Recording and pre-processing of the EEG data were performed with a BrainAmp DC amplifier and the BrainVision Recorder software (Brain Products, Herrsching, Germany).

For the ERP analysis the data were band-pass filtered offline with high-pass frequency of 0.1Hz and a low-pass frequency of 35Hz and re-referenced to linked mastoids. Data were segmented into epochs; for R1 the 1100ms from 100ms prior to stimulus onset to 1000ms after stimulus presentation and for R2 the 1000ms from 100ms prior to stimulus onset to 900ms after stimulus presentation. The Grattan and Coles method (Grattan et al., 1983) was used for ocular correction, and baseline correction was applied using a window from 100ms to 0ms before the stimulus. Epochs were also excluded automatically if any values exceeded a threshold of ± 100μV, resulting in a rejection rate of ~10%.

Based on inspection of averaged data, peak event-related potential (ERP) amplitudes for the anterior N1 component were computed at the F1 and F2 electrodes in the interval 100ms to 180ms after stimulus onset. For the posterior N1 component amplitudes were computed at the PO3 and PO4 electrodes in the interval 100ms to 200ms. This extended time interval for the posterior electrodes is because the time-course of the N1 varies across the scalp from anterior to posterior. Immediately after the clearly observable anterior N1 ERPs the EEG traces varied considerably in the different stimuli categories and across participants. Consequently, for the anterior N2 component at the F1 and F2 electrodes a peak-to-peak measurement was taken from the most positive preceding peak (P2) to the most negative following peak (N2). The P2 was calculated as the local peak between 180ms and 260ms after stimulus onset and the N2 was calculated as the local peak between 280ms and 370ms after stimulus onset. For each individual participant's set of data an earlier P2 peak corresponded with an earlier N2 peak and a later P2 peak corresponded with a later N2 peak. The aim was to standardize the measurement between categories by observing the amplitude between the peaks. It was planned to repeat the time windows used in the earlier study, with young adults (Chapter 3), but on inspection of all individual results, greater amplitudes appeared later in data from the older adults.

Repeated-measures mixed-design ANOVAs were carried out assessing differences in N1 and N2 amplitudes. The two participant groups (stroke survivors and neurologically healthy age-matched controls) were the between-subjects factor, the within-subject factors being posture (left- and right-hand

forward), presentation rate (R1 and R2), hemisphere (left and right) and the stimulus categories (power grip, precision grip and empty desk). Comparisons were sought between manipulable objects that were not necessarily tools (a box and a sweet were included) against no object (on the same desk backdrop) to discover whether resulting EEG recordings for manipulable objects showed activity similar to that found more readily in previous studies for tools only (e.g. Proverbio et al., 2011; Righi et al., 2014). Analysis was undertaken to compare any differences between the two categories of objects in relation to the type of grip they might afford (precision grip or power grip) as well as between each category of object and the empty desk. The Greenhouse-Geisser correction was used to correct for any violations of sphericity.

EEG accurately measures microvoltage changes across the scalp from the underlying cortex. However, it is more challenging to locate the source that causes this cortical neuronal activity. To solve the problem, BrainVision Analyzer software uses Low Resolution Electromagnetic Tomography (LORETA) which provides the distribution of the electrical activity throughout the three dimensional brain. Although there is no unique solution to this inverse problem, LORETA takes into account neighbouring voxels having similar activity and is able to calculate the current density at each voxel in the brain (Pascual-Marqui et al., 1994). The Analyzer LORETA solution space comprises 2394 $7mm^3$ voxels with pre-defined brain locations restricted to cortical grey matter and hippocampus. The source space is based on the Montreal Neurological Institute (MNI) template MNI-305, being the digitized averages of MRI scans from 305 subjects, co-registered to the Talairach atlas (Talairach & Tournoux,

1988). LORETA uses a three-shell spherical head model registered to Talairach atlas based on the MNI brain.

As this averaged brain system cannot account for area of lesion, source location was not carried out on the stroke survivor group. R1 produced greater voltages than R2, so source analysis was carried out on N2 data for R1 only. Regions of interest (ROIs) were chosen with an emphasis on sources reported in Proverbio et al. (2011), that is, Brodmann Area (BA) 6 and Brodmann Area (BA) 3 which were found to be activated by viewing tools only and not by other objects. In addition, due to extensive findings suggesting the involvement of dorsal and also ventral streams from initial object observation to reaching and grasping actions (Almeida, Fintzi, & Mahon, 2013; Grèzes et al., 2003; Karnath, 2001; Milner & Goodale, 2008; Rizzolatti, Fogassi, & Gallese, 2002; Rizzolatti & Matelli, 2003; van Polanen & Davare, 2015; Ward & Frackowiak, 2003) it was considered worthwhile to investigate recruitment of areas within these streams. Therefore, additional ROIs were tested, namely the middle occipital gyrus (BA19) the inferior parietal lobule (BA40) and superior parietal lobule (BA7) the middle temporal gyrus (BA39) and inferior frontal gyrus (BA44). Initially, to ascertain specific voxel locations for each ROI, the LORETA grand average of all control participants was visually examined within the N2 peak time-frame for greatest overall current density. This information allowed current density in A/mm^2 to be computed for each of the stimuli conditions (power-grip object, precision-grip object and no object) at the latency observed for each participant's own, individual N2 peak. ANOVAs were carried out separately for each BA in each posture.

6.3 Results

Analyses focused on both N1 and N2 components. The prominent N1 negative component was assessed for differences in both anterior and posterior activity. Of greater interest, however, was the anterior N2, previously inferred to reflect the presence or absence of an affordance (Allami et al., 2014; Proverbio et al., 2011; Rowe et al., 2017). Neuroplasticity in stroke survivors may alter the underlying neural networks producing the voltage changes measured by EEG. Therefore it was considered reasonable to also investigate the source of the cortical measurements during the N2 time-window (but only in controls). All pairwise follow-ups were Bonferroni corrected.

6.3.1 The N1 Component

At posterior sites, PO3 and PO4, the posture by presentation rate by hemisphere by stimulus category by participant group (2x2x2x3x2) ANOVA revealed only a significant main effect of stimulus category, $F(2, 46) = 4.496$; $p = .016$, $\eta p^2 = .164$. Mean voltage was -1.782μV for power-grip objects, -0.838μV for precision-grip objects, and -1.151μV for the empty desk. Pairwise follow-ups revealed significant differences just between the power-grip object stimuli and precision-grip object stimuli with $p = .010$.There were no significant interactions involving stimulus category.

At anterior electrodes F1 and F2 (see Figure 6.1) the ANOVA revealed a main effect of stimulus category $F(2, 46) = 16.630$; $p = .001$, $\eta p^2 = .429$. There was also a significant interaction between presentation rate and stimulus category $F(2, 46) = 4.020$; $p = .041$, $\eta p^2 = .149$. Follow up one-way ANOVAs across

stimulus categories were significant for both presentation rates. For the 0.5Hz (R1), follow-up pairwise comparisons showed that there were significant differences between each object category and the no object category; between the power-grip object stimuli and no object $p = .010$ and between the precision-grip object stimuli and the no object stimuli $p < .001$. For the 1Hz presentation rate (R2) there were significant differences between the precision-grip object and the power-grip object stimuli, $p = .028$ and between precision-grip object and the no object stimuli, $p < .001$. Essentially, in R1 the microvolt means for the no object category were considerably smaller than those for the other categories but in R2 the microvolt means for precision-grip objects were considerably larger than those for the other categories. There were no further interactions involving stimulus category.

6.3.2 The N2 Component

Here the 2x(2x2x2x3) ANOVA showed just one significant interaction; that of posture by hemisphere by participant group with $F (1, 23) = 6.934$; $p = .015$, $\eta p^2 = .232$. The same 2x2x2x3 ANOVA run separately for each participant group revealed a significant interaction between posture and hemisphere for the stroke participant group, $p = .045$ but pairwise follow-ups were not significant. There was no such interaction for the control group.

There was a significant main effect of timing, $F (1, 23) = 26.517$; $p <.001$, $\eta p^2 = .536$ with the N2 for the 0.5 Hz presentation rate having the larger amplitude; 4.838μV compared to 3.699μV for the 1 Hz rate. Most relevant for this investigation was a significant main effect of stimulus category,

F (2, 46) = 75.702; $p < .001$, $\eta p^2 = .767$. The actual means were, for power grip objects, 5.796µV; for precision grip objects, 5.145µV; for no object (empty desk), 1.864µV. Pairwise follow-ups showed significant differences between power grip object stimuli and the no object stimuli; $p < .001$ and, likewise, between precision grip object stimuli and the no object stimuli; $p < .001$.

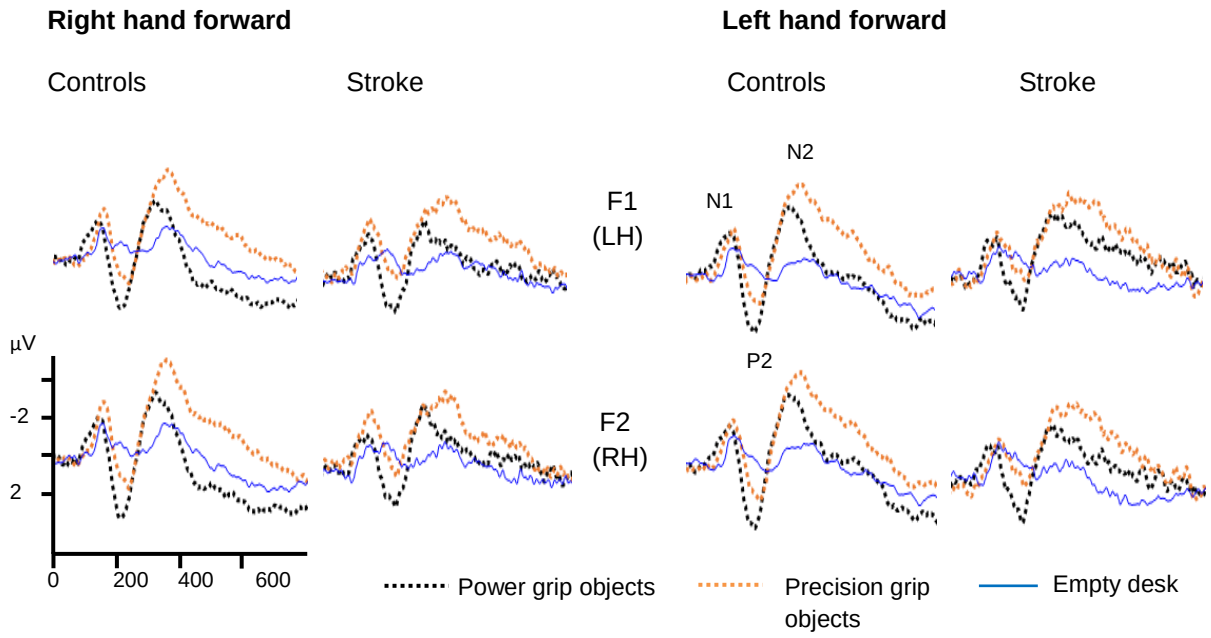


Figure 6.1. Waveforms at F1 and F2 electrodes from both participant groups for both postures at the 0.5Hz presentation rate. The N2 peak (and the difference between P2 and N2) is noticeably greater for both object stimulus categories compared to the empty desk (no object category). LH = left hemisphere, RH = right hemisphere

There was no significant difference between the power-grip and precision-grip object categories. There were no other main effects. Figure 6.1 shows the waveforms for each stimulus category for both sets of participants. In all cases, the N2 peak (and, indeed the difference between the preceding P2 peak the N2) is larger (more negative) for each of the object categories compared to the no object category.

6.3.3 Source Analysis

The grand average from all control participants was visually examined within the N2 peak time-frame. For the LORETA calculations, voxel coordinates at the centre of up to a 5mm sphere were identified at the greatest current density for each ROI. These are shown in Table 6.3.

Table 6.3. Regions of interest for source analysis with voxel located at centre of sphere with between 3mm and 5mm radius.

Region	**Left Hemisphere Coordinates**			**Right Hemisphere Coordinates**			**BA**
	x	y	z	x	y	z	
Frontal lobe, precentral gyrus	-45	3	43	46	3	43	6
Parietal lobe, postcentral gyrus	-59	-18	29	60	-18	29	3
Frontal lobe, inferior frontal gyrus	-52	10	15	53	10	15	44
Temporal lobe, middle temporal gyrus	-45	-74	15	46	-74	15	39
Parietal lobe, inferior parietal lobule	-38	-56	50	39	-53	50	40
Parietal lobe, superior parietal lobule	-31	-67	57	32	-67	57	7
Occipital lobe, middle occipital gyrus	-31	-88	8	39	-84	8	19

Then, separately, for each ROI and for all control participants at the latency relating to their own N2 peak in the R1 condition, current density was computed at the same voxel coordinates for each of the stimuli conditions (power-grip object, precision-grip object and no object). To discover whether there were any

significant differences in sources of brain activity, posture by hemisphere by stimulus category (2x2x3) ANOVAs were carried out separately for each ROI. There was no main effect of posture but there were significant main effects of stimulus category at each ROI and a main effect of hemisphere at BA3, BA7, BA19 and BA44. There were significant interactions only at BA39. Reporting each BA individually, results are shown in Table 6.4.

Table 6.4. Brodmann Areas and ANOVA main effects. Symbols > and < show the direction of the significant differences with p < .050; symbols **>** and **<** indicating p < .010. *Further interaction effects described in main text**.**

Area	Main effect - Hemisphere	Main effect - Stimulus
BA6	none	power grip > no object
BA3	left **>** right	power grip **>** no object < precision grip
BA44	left **>** right	power grip **>** no object < precision grip
BA40	none	power grip **>** no object **<** precision grip
BA7	left **>** right	power grip **>** no object < precision grip
BA19	left > right	power grip > no object < precision grip
BA39*	none	power grip **>** no object **<** precision grip

For BA39 there was also a significant interaction between posture, hemisphere and stimulus categories, $F(2, 28) = 6.789$; $p = .004$, $\eta p^2 = .327$. Follow-up 2x3 ANOVAs (hemisphere x stimulus category) for each posture separately and (posture x stimulus) for each hemisphere separately showed only a main effect

of stimuli; generally current density for both types of object category was significantly greater than for the no object category. This was the case for each posture and for both hemispheres.

For each ROI all differences between stimulus categories were between either or both of the object stimulus categories and the no object stimulus category. In all of these cases, the current density was less for the no object category. There were no significant differences in current density when participants viewed power grip objects compared to viewing precision grip objects.

6.4 Discussion

This experiment investigated object-related brain activity in stroke survivors with ongoing upper limb deficits, relative to that in neurologically healthy people of a similar age. Participants were presented with three-dimensional photographs of either power grip or precision grip objects on a desk, or just the empty desk, and their bodies positioned so as to vary whether those objects could be reached easily with the dominant hand (while holding visual stimulation constant). All healthy controls and most stroke survivors had right-hand dominance although some who were premorbidly right-handed had developed compensatory left-hand dominance. Brain activity was recorded while participants observed stimuli presented at a rate of 0.5Hz and also presented at a rate of 1Hz.

Assessments were made of late (N2) and early (N1) object-evoked activity in both the stroke survivors and the healthy controls. However, chief expectations

related to the N2. The main effect of stimulus category was the key result, with greater activity recorded when viewing the objects compared to viewing the empty desk, clearly suggesting an affordance effect. Although unable to replicate the anticipated enhancement of this stimulus-category effect when paired with an appropriate (right-hand forward) posture, nonetheless it was found that the N2 is modulated by the presence of manipulable objects, and, importantly, this result extended to stroke survivors. If affordances can be generated in those recovering from a stroke, a basic-science justification for the therapeutic presentation of objects during rehabilitation can be said to exist.

Affordances are, by definition, a motoric rather than purely visual effect, and the stimuli contained substantial visual differences in addition to their implications for action. Hence a more robust indication of an affordance would have come from a significant interaction between posture and stimulus category, especially if found in the dominant left hemisphere, as in the previous experiment (Chapter 3). However, much younger volunteers were recruited to that study (mean age 28 years) whereas in the current study with older participants (mean age across both stroke and healthy control groups 69 years), reduction in hemispheric asymmetry due to increasing age must be considered (Cabeza, 2002; Graziadio, Nazarpour, Gretenkord, Jackson, & Eyre, 2015; Ward & Frackowiak, 2003; Wu & Hallett, 2005; Zimerman, Heise, Gerloff, Cohen, & Hummel, 2014). Due to the presence of brain lesions in the stroke group, exact replication of earlier results would be improbable. However, for the control subjects, greater bilateral activity (and the implied greater ambidexterity) could explain why for the N2 there was no significant posture by stimulus category interaction, nor any significant differences between hemispheres. Ward and Frackowiak (2003)

performed a comprehensive behavioural and fMRI study, recruiting 26 subjects with ages ranging from 26 to 80. Participants carried out a motor grip task, squeezing two bars together to percentages of their own individual maximal voluntary contraction (MVC). The dominant right hand and non-dominant left hand were tested in separate sessions. fMRI showed age-related differences, some of which identified greater right-hemisphere activity during dominant hand grip for older compared to younger participants. The authors believed this lessened ipsilateral cortical deactivation was due to reduced transcollosal inhibition, caused by advancing age.

Turning to the posterior N1 component, results showed differences between the two object categories. This was contrary to the earlier study with no significant differences between any of the three stimulus categories. Even so, as there were no differences between either object category and the no-object category it would appear that each type of object was, in fact, visually processed in a broadly similar manner to the empty desk.

However, for the anterior N1 component there were significant differences between the no-object stimulus category and each of the two object categories (at least for the slower 1 Hz presentation rate). In fact, the greatest difference in microvolts for the N1 peak occurred between no object and the small, precision grip objects, suggesting that this result was not driven by visual complexity. Might affordances be evident as early as the anterior N1?

A recent TMS study (Franca et al., 2012) revealed facilitation in FDI compared to ADM and opponens pollicis (OP) muscles when actual small objects were

presented. Previous studies had provided evidence favouring right-hand representation of precision grip over power grasp (Vainio, Ellis, Tucker, & Symes, 2006; Vainio et al., 2007) so the authors chose objects that normally evoke a thumb to index finger precision grip. Participants closed their eyes until cued by a sound. Shortly thereafter a box was illuminated for 300ms, showing the presence or absence of an object. A TMS pulse was delivered over left motor cortex at 120ms, 150ms or 180ms after stimulus onset. EMG analysis revealed a significant main effect of 'object presence' for the FDI only, and although the timing of delivery of TMS for FDI was not significant per se, further analysis showed a significant difference between object and no object at the 120ms time point but not at the later times. In the current experiment, the N1 amplitude between 100ms and 180ms was correspondingly larger for the object categories compared to the no object category.

While the N2 has already been identified as an indicator of affordance (Allami et al., 2014; Proverbio et al., 2011) the anterior N1 result (comparable to the facilitation found by Franca et al. (2012)) would suggest an earlier affordance onset. The EEG data and analysis differed from that of their TMS experiment as it was averaged for each hemisphere, over 360 trials for each participant with two different stimulus presentation rates in two postures and across participants. Consequently, identifying a specific time-point of greatest N1 amplitude in this data would not necessarily correspond with the result of Franca et al. (2012) where TMS pulses were delivered at three distinct time-points. However, like other TMS studies, e.g., Buccino et al. (2009) and Makris et al. (2011) where facilitation was present at 200ms and 300ms respectively,

the N2 observed between 280ms and 370ms may signify continuation of an already existing action affordance.

Like the previous study in young healthy adults, results again complement and extend those of Proverbio et al. (2011) and Proverbio (2012) who investigated EEG markers for automatic object-action priming. In their work, pictures of objects affording action were contrasted with pictures of objects that did not afford any actions, and effects were found in the N2 (and later), with a swLORETA analysis linking this effect to motor regions of the brain. However, the current study included the additional element of comparison between healthy older-age adults and neurologically damaged older adults. LORETA analysis of the healthy group, whilst unable to completely reproduce the findings of Proverbio et al. (2011), did indicate source activity in dorsal and ventral streams previously found to be recruited when grasping objects.

In relation to the 2011 study, as well as greater current in the left hemisphere, current density differences were also found here between power-grip object stimuli and no object stimuli in the premotor cortex (BA6) and, again, significant differences between each class of object stimuli and the empty desk arose in the primary somatosensory area (BA3). The left-hemispheric bias, which was not apparent in the initial evoked-potential analysis, is suggestive, and allows assertion of a motoric contribution to the N2, as participants were right handed and the stimuli contained no hemispatial biases. However, the lack of interactions with object category means that such assertions must remain cautious.

The BA40 coordinates x = -38, y = -56 and z = 50 for left hemisphere and x = 39, y = -53 and z = 50 for right hemisphere correlate closely with the AIP coordinates found by Culham et.al. in their 2003 MRI study on visually guided grasping (these were x = -38, y = -48 and z = 52 for left hemisphere and x = 40, y = -50 and z = 50 for right hemisphere). That study found these areas to be significantly more activated by making an actual precision grip rather than simply by reaching forward to touch an object with the knuckles. In the current study while there was no significant difference between the two object categories, the current density was greater for both of the object categories than the no object category which would accord with findings of Culham et al. (2003). In fact for BA3, BA39, BA40, BA44 and BA19 when participants viewed objects in either of the object stimulus categories, there was significantly greater current density than when they viewed the no-object stimuli.

Although EEG source analysis has limited spatial capabilities, it may be concluded from these results that the object stimuli produce both dorsal and ventral stream activation. From the middle occipital gyrus onwards it could be argued that significant differences in current density followed a path dorsally, activating both the anterior intraparietal area (AIP) and the superior parietal lobule, the precentral gyrus and premotor cortex. Ventrally, the middle temporal gyrus was recruited as was the ventral part of the lateral premotor cortex. However, while all analyses were theoretically motivated, there were a large number of them, so some effects are likely to be false positives.

Hand dominance was not fully investigated here but would have been explored further for a larger stroke survivor cohort. Each stroke participant regarded their

right hand has their dominant hand prior to stroke. Two participants with left-hemisphere stroke still retained use of their right hand (LI index 43 and 56) and right-hand dominance was preserved for the two participants who had right-hemisphere stroke. Although the heterogeneity of stroke patients used here represents an important limitation for the study, it remains noteworthy that there were no significant hemispheric differences in N1 and N2 waveforms between stroke and control participants. If stroke patients were, for example, now generating affordances only in their intact hemisphere, it could be anticipated that there would be some change in waveform topography. In any event, for both participant groups, reduction in hemispheric asymmetry due to increasing age must be considered (Cabeza, 2002; Graziadio et al., 2015; Ward and Frackowiak, 2003; Wu and Hallett, 2005; Zimerman et al., 2014). This may explain why posture did not modulate the affordance effect here, in contrast to the previous work with young adults (Chapter 3). Perhaps the positioning of the dominant hand relative to an object has less functional relevance in the mature brain.

As well as the handedness issue, the stroke survivor cohort contained some participants with left and some with right hemisphere damage. Additional analysis of all the stroke participants' data, comparing ipsi- and contra-lesional hemispheres separately might have given more insight into brain activity after stroke. This could have been achieved by direct data comparisons to evaluate the amount of activity occurring over each hemisphere. Alternatively, simply relabelling the electrodes of those with right hemisphere damage to match the ipsi-lesional and contra-lesional hemispheres of the left-brain damaged participants, prior to analysis, could have produced this result. However, due to

such a small cohort of just ten (two with right hemisphere damage), carrying out such analysis may not have contributed any substantially valuable information.

6.5 Conclusion

Passively observing manipulable objects results in regional brain activity consistent with the existence of automatic affordances within the motor system. Here it is shown that between 280ms and 370ms after stimulus onset the evoked ERP N2 component differed between an empty desk and the two categories of manipulable object (power grip and precision grip) placed on that desk. Source analysis indicated that this involved motor areas in dorsal and ventral regions, with a left-hemispheric bias. There appeared to be little distinction between the type of manipulable object. Examination of the anterior N1 component, between 100ms and 180ms also resulted in significantly larger peak amplitudes for each object category compared to no object and, again there were no significant differences between the two object categories. Taken together, the above time scales for the generation of an affordance are in agreement with previous studies (Allami et al., 2014; Franca et al., 2012).

Importantly, results from the stroke survivors were very similar to those of the age-matched controls, suggesting the occurrence post-stroke of motoric brain activity attributable to the properties of objects. However, each individual in this cohort was at least 2 years post-stroke without a declared diagnosis of apraxia as a reason for the decreased upper limb function. Employing the Test to Measure Upper Limb Apraxia, known as TULIA, would have been valuable.

Such assessment of stroke participants on transitive, intransitive and pantomiming gestures could have provided evidence whether, and to what degree, some of the upper limb deficits were, in fact, due to apraxia.

Further EEG studies with fully assessed apraxic participants would be advantageous to determine if affordance-like activity is present in this condition. Additional research may discover any benefit of timed object introduction and removal in recovery of upper limb function in the acute phase of stroke. For this purpose, observation of the 1 second presentation rate producing clearer results than the 0.5 second rate could be a factor incorporated in some of the virtual reality computer games used in stroke rehabilitation.

Brain activity observed in stroke survivors comparable to that in age-matched controls led to an investigation with neurologically healthy participants for evidence of cortical changes through repeated passive viewing of manipulable objects. This pilot study is reported in the following chapter.

Chapter 7

Piloting affordances as therapy:

Cortical plasticity in healthy controls

7.1 Introduction

The EEG experiment reported in Chapter 3 provided new information on the time-course of affordances, defined by a combination of the N1 and N2 ERP components. In addition, the posture modulation revealed hemispheric differences implying specific motoric activity when right-handed participants viewed manipulable objects. The subsequent EEG experiment (Chapter 6), began to answer the question of whether affordances may play a part in upper limb stroke rehabilitation. Recordings from stroke survivors followed a similar pattern in respect of N1 and N2 ERP components to the age-matched healthy cohort. To further address this question, a TMS pilot study was devised to ascertain if repeatedly viewing manipulable objects could enhance corticospinal motor activity even without a conscious action plan.

7.2 Background

Effectiveness of interventions which promote recovery of motor function following brain injury can be assessed by observing patient motor output. Assessing corticospinal projections from the primary motor cortex to hand muscles can further inform the reliability of such therapies.

Unlike single-pulse or paired pulse TMS, as a form of therapy, repetitive TMS (rTMS) may be administered at a rate of 1Hz for up to 20 minutes per session (Grefkes et al., 2010; Kobayashi, Hutchinson, Théoret, Schlaug, & Pascual-Leone, 2004; Lefaucheur, Drouot, & Nguyen, 2001; Mello et al., 2015) or even at a far greater rate of 10Hz for shorter durations (e.g. Lefaucheur, Drouot, Ménard-Lefaucheur, Keravel, & Nguyen, 2006; Lefaucheur et al., 2001). Such rapid stimulation has been used to reinstate intracortical inhibition for patients with unilateral chronic hand pain (Lefaucheur et al., 2006). Similarly, rTMS can be used over the contralateral or ipsilateral motor hotspot to affect dexterity in healthy controls (Kobayashi et al., 2004) and to promote recovery of the paretic hand after stroke (Grefkes et al., 2010; Mello et al., 2015). Duration of benefits are variable with corticospinal changes/improvements sometimes lasting less than 20 minutes after sessions (Kobayashi et al., 2004; Mello et al., 2015) but may still be evident up to a week later (Lefaucheur et al., 2001).

By contrast, single-pulse TMS is delivered at around 0.2Hz and studies have tended to focus on how sets of stimuli immediately inhibit or facilitate motor activity without any lasting effect. Visual or audio stimuli are presented and a TMS pulse at a set intensity is delivered milliseconds prior to, or after, the onset of the stimulus (e.g. Bartoli et al., 2014; Buccino et al., 2009; Cardellicchio et al., 2011; Cattaneo et al., 2005; Franca et al., 2012; Makris et al., 2011, 2013; McNair, et al., 2017).

However, single-pulse TMS can also map motor areas by stimulating at different positions and recording evoked MEPs from different hand muscles (e.g. Julkunen, 2014; Kraus & Gharabaghi, 2015; Wassermann, McShane,

Hallett, & Cohen, 1992). A common method has been to stimulate at around 10% above RMT over a grid of 1cm squares. Provided three consecutive pulses produce MEPs above, say 20μV, then the part of the cortex being stimulated relates to the muscle from which MEPs are recorded (Mortifee, Stewart, Schulzer, & Eisen, 1994). This type of mapping is a useful tool for optimal positioning to identify morphological differences between individuals (Coppi et al., 2014; Kraus & Gharabaghi, 2015). Coppi et al. (2014) mapped contralateral and ipsilateral motor cortices for the abductor pollicis brevis (APB) and the abductor digiti minimi (ADM) in right-handed young adults (mean age ~ 25 years) and right-handed older adults (mean age ~ 61 years). In the older group, the APB map on the right hemisphere was significantly reduced compared to the younger group although for the ADM there were no significant map differences.

However, mapping multiple locations may not be necessary, as by increasing the intensity of TMS pulses at a single location it is possible to obtain input output (I/O) recruitment curves correlating stimulation intensity with MEP size, which may then be used to construct a sensitive measure of corticospinal excitability (Devanne, Lavoie, & Capaday, 1997; Komssi, Kähkönen, & Ilmoniemi, 2004; Talelli, Ewas, Waddingham, Rothwell, & Ward, 2008; Talelli, Waddingham, Ewas, Rothwell, & Ward, 2008; van de Ruit & Grey, 2016).

Such input/output recruitment curves can be repeated to detect changes in cortical organisation after brain injury (Kuppuswamy, Clark, Turner, Rothwell, & Ward, 2015; Stern et al., 2016; Zewdie, Damji, Ciechanski, Seeger, & Kirton, 2017) and after targeted training in healthy controls (Christiansen, Larsen, Grey,

Nielsen, & Lundbye-Jensen, 2017; Goldsworthy et al., 2016). Kuppuswamy et al. (2015) measured post-stroke fatigue through self-report, functional screening tests and TMS paradigms including paired-pulses, to detect intracortical inhibition, and via single-pulse intensity mapping. Results correlated low cortical excitability with higher RMT and also with higher levels of fatigue in stroke survivors.

Christiansen et al. (2017) investigated changes in the ipsilateral hemisphere after motor training of the participants' right hand. Training consisted of a visuomotor task in the style of a video game where bricks were knocked down. Participants were all neurologically healthy. Eleven were assigned to a group where difficulty of task was progressive (PT group); for the other twelve difficulty of the task was not progressive (NPT group). All were assigned to train for 28 minutes during each of 18 sessions over a 6-week period. TMS intensity mapping occurred prior to training, after the 6 weeks and then again 8 days later (Retention 1). A final mapping was carried out after 14 months (Retention 2). At 6 weeks and at Retention 1 and 2 participants also played the video game with their left hand. Recruitment curves of MEPs from the left ADM were significantly increased for the PT group compared to the NPT group at 6 weeks and at Retention 1 but this effect was not present at Retention 2. These results were mirrored by those of the left hand motor task with the PT group significantly out-performing the NPT group at 6 weeks and Retention 1.

Cortical reorganisation following the training of a healthy motor system is a striking finding. However, this thesis was in part motivated by the possibility that just presenting objects might generate affordances that could act in the manner

of a training stimulus. Discovering any motor priming occurring in healthy subjects from passively viewing manipulable objects could inform future stroke interventions. Therefore, an approach based on previous TMS mapping studies was adopted in a pilot study. From current literature, it appears that cortical reorganisation following this kind of “affordance therapy” has not previously been assessed.

7.3 Current Experiment

To test whether affordances evoked by passive stimulus viewing might lead to persistent changes at a corticospinal level, TMS pulses at increasing intensities, being percentages of each individual’s resting motor threshold (RMT), were delivered over the contralateral cortex. This provided a baseline for size of MEPs obtained from two hand muscles, FDI and ADM, and was followed by two interventions; 1) passively viewing stimuli depicting precision-grip objects and 2) passively viewing stimuli depicting power-grip objects. The intensity mapping was then repeated to determine any change in MEP amplitude attributable to intervention. The intention was to discover whether such intervention could enhance corticospinal activity to produce greater MEPs in the muscle after viewing objects congruent with use of that muscle compared to viewing incongruent objects. Theoretically, this could be achieved by normal single-pulse TMS, but sometimes effects are only apparent from intensities at specifically low or high percentages above RMT. For example Goldsworthy et al. (2016) used I/O curves to investigate effects of theta burst stimulation (TBS) administered both intermittently (iTBS) and continuously (cTBS). iTBS is likely to facilitate and cTBS to inhibit cortical excitability. Lower stimulation intensities

revealed consistently facilitated MEPs after iTBS at 110% RMT whereas depressed MEPs induced by cTBS were best identified at or above 150% RMT. Therefore the approach adopted for this pilot was to explore physiological differences for TMS pulses delivered at increasing intensities, in order to maximise sensitivity to any changes, but with a range of intensities selected to be appropriate for a non-medical research setting.

7.4 Materials and Methods

7.4.1 Participants

Six participants were recruited from inside and outside of the University through City, University of London Sona System online research recruitment (2 male, 4 female, mean age 32 years 3 months, SD 4 years 2 months). Each was given full information regarding the safety aspects of TMS at least one day prior to attending. They also completed a health screening questionnaire immediately prior to the session to confirm suitability for this form of monitoring brain activity (example questionnaire in appendix A). All had normal or corrected-to-normal vision with no history of neurological illness and all were right-handed as verified by the Edinburgh Handedness Inventory, adapted from Oldfield (1971). The study was approved by City, University of London Ethics Committee and participants gave written consent. Volunteers were paid £8 per hour for their time with sessions lasting approximately one and a half hours. At the end of the experimental session, participants were given a debrief form confirming the number and frequency of pulses administered and requesting feedback for any adverse effects during the experiment. No participant recorded any such effects (sample form in appendix B).

7.4.2 Stimuli

A subset of independently rated 3D photographs of 40 objects (full details of assessment of stimuli is reported in Chapter 3) was chosen which contained good exemplars of objects affording either a forefinger and thumb precision grip or a whole hand power grip (i.e. consistently rated “always” for the relevant grip and predominantly rated 2/2 on a familiarity scale). For the experiment, these stimuli were used to construct two object stimulus categories. The first consisted of one picture of each of six objects, which would normally be held in a precision grip (wax crayon, sweet, pencil sharpener, roll of sellotape, battery, glue tube). The second consisted of one picture of each of six objects which would normally be held in a power grip (hairbrush, trowel, box, pliers, antiperspirant can, liquid soap container).

7.4.3 Design and Procedure

Baseline MEPs from the right hand FDI and ADM were simultaneously recorded from 15 TMS pulses delivered at a rate of no greater than 0.2Hz, over the left hemisphere for each of five stimulation intensities. These were 105%, 110%, 115%, 120% and 125% of the individual participant’s resting motor threshold (RMT) given in ascending order of intensity. Then, similarly to the TMS experiment described in Chapter 4, participants were seated in front of a mounted stereoscope, approximately 45cm from a CRT monitor refreshing at 100 Hz. Initially, participants were allowed time to adjust the viewer so that they observed a single object in three dimensions. Again, for this calibration a tennis ball and a dishwashing sponge were presented in alternation. These two

objects were used only for re-calibration purposes throughout the experiment and were not part of the object stimuli forming the interventions.

There then followed for 8 minutes an intervention of type 1 (or 2) where each of 6 precision (or power) grip objects were viewed in a randomised order for one second after a one second fixation cross, with 40 trials of each object making 240 trials altogether. There was no TMS carried out during this viewing period.

Afterwards, the 15 pulses at each intensity were repeated. As it was believed that any affordance effect present immediately after the viewing session might soon dissipate, a ‘top up’ viewing was initiated with 3 trials of each 6 objects viewed between each increase in TMS intensity. After stimulating at the highest intensity the above was repeated with the other intervention in a crossover design (i.e. order of conditions was counterbalanced across participants). Unlike all previous experiments described in this thesis, the posture modulation was not included here as the main objective was to see if *any* affordance effect may be sustained (rather than how it may be altered by posture).

7.4.4 EMG Recording

As in the earlier TMS experiment two surface Ag/AgCl EMG electrodes (22 x 28 mm, part No.SX230FW, Biometrics Ltd., Ladysmith, VA) were placed on the right hand, approximately 2–3 cm apart over the ADM muscle and a nearby reference site (just above the styloid process of the right ulnar). Two other electrodes were similarly placed to record from the FDI muscle of the same hand with further ground electrodes attached to the wrist. EMG (band-pass filtered 20–450 Hz) was collected at 1000 Hz via a 13-bit A/D Biometrics

Datalink system (version 7.5, Biometrics Ltd.) and stored on a second dedicated PC. Digital data were exported and analyzed offline using MATLAB (The Mathworks, Natick, MA). To achieve the greatest number of usable MEPs, the EMG was also sent to a speaker to detect separate FDI and ADM muscle activity which might represent pre-activation and render the MEP invalid. Two individual speakers (one for each muscle) served as a prompt for participants to relax the relevant muscle.

7.4.5 TMS Protocol

Individual's motor hotspots were identified with the aid of MRI template anatomically-guided hardware and software, Visor 2 (ANT Neuro, The Netherlands). To detect the hotspot, first the coil was placed on the scalp roughly above the left primary motor cortex. It was then moved by approximately 1cm in each direction until the greatest MEPs were produced. Location on the scalp was identified and recorded by the software to enable TMS coil position to be maintained throughout the experimental trials. During this process, stimulation began at 30% of the stimulator's output and was increased by 5% increments until MEPs were reliably recorded. Then the output was decreased in 1% steps. The resting motor threshold (RMT) was observed and noted as the lowest stimulation value when at least 5 out of 10 consecutive TMS pulses produced MEPs from both the FDI and ADM of 50μV or more while the participant's hand was fully relaxed. Throughout the intensity mapping trials, the pulses were maintained at a frequency of ≤ 0.2 Hz.

7.4.6 EMG Measurement and Analysis

Each individual MEP was verified using customized MATLAB software allowing semi-automatic rejection for pre-activation. Throughout the 200ms prior to the TMS pulse MEPs were rejected if there was any activity recorded from either muscle with peak-to-peak EMG excursion of ≥ 50μV. MEPs produced from stimulation of the FDI always tended to be greater than those produced from the ADM, most likely because the FDI is more regularly used in everyday activities and thus better represented in M1. This did not affect results as the experimental question related to changes in MEP amplitude for each muscle independent of the other.

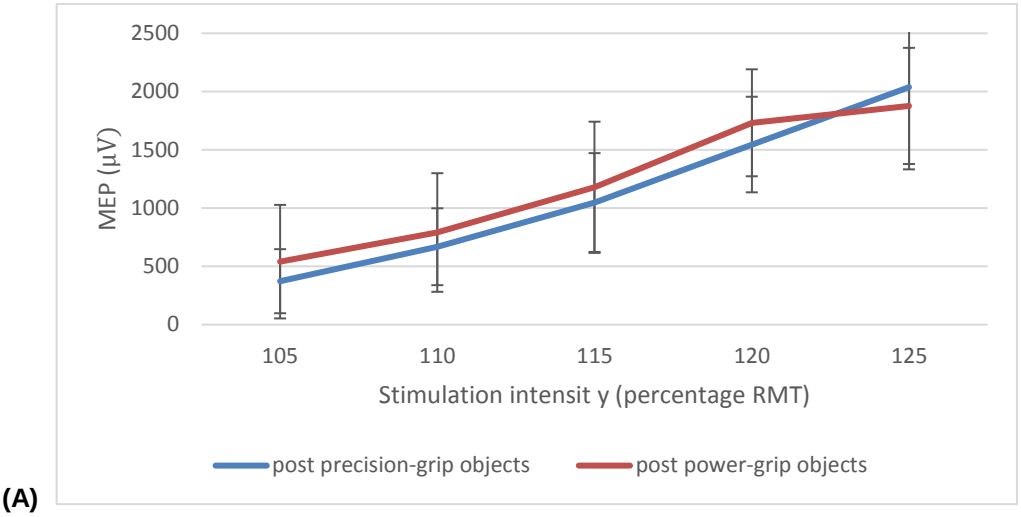
7.5 Results

RMTs as a percentage of the stimulator output were 50 for two participants, and 45, 54, 56 and 64 for the remaining four. For the safety and comfort of the participant with the higher RMT of 64, instead of starting at 105% RMT and increasing in steps of 5%, the maximum stimulation intensity was 115% of their RMT but the increase was in equal graduations; 103%, 106%, 109%, 112% and 115%. Less than 10% of all trials were discarded due to pre-activation or poor signal to noise ratio but for Subject 3, an execution error meant that the baseline MEPs at 105% RMT (15 trials) were not recorded. (For results relating to Figure 7.2, data for 105% RMT were extrapolated from this participant's other baseline data). The interest was specifically for effects post interventions i.e. greater MEPs produced by observing objects congruent for muscle use. Therefore, although baseline MEPs were recorded to ensure that each participant was comfortable with the increasing intensities, these were not

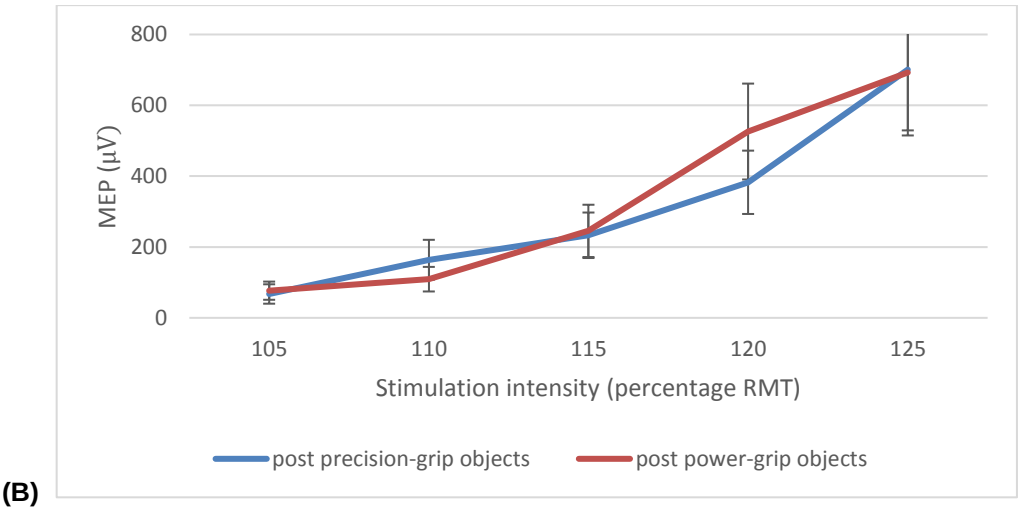
incorporated in the main analysis. In all analyses the Greenhouse-Geisser correction was used to correct for violations of sphericity and for pairwise comparisons the Bonferroni correction was used.

A 2x2x5 ANOVA (muscle by intervention by intensity) was carried out on median MEP scores. I/O recruitment curves for FDI muscle (top) and ADM muscle (bottom) are shown in Figure 7.1. The curves represent MEPs after intervention 1 when participants viewed precision grip objects that would normally activate FDI (post FDI) and after intervention 2 when they viewed power grip objects that normally activate ADM (post ADM).

The only significant main effect was for intensity $F(4, 20) = 14.630$; $p = .007$, $\eta p^2 = .745$ and the only significant pairwise differences were between the second and fourth stimulation intensities, with $p = .030$. The interaction of most interest was between muscles and interventions, i.e. the effect on the FDI muscle and the effect on the ADM muscle post FDI and post ADM but this was not significant.



(A)

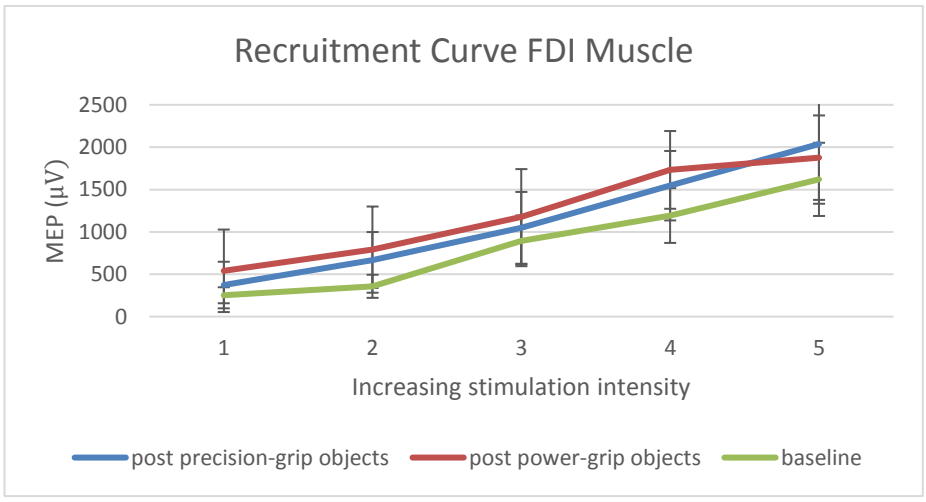


(B)

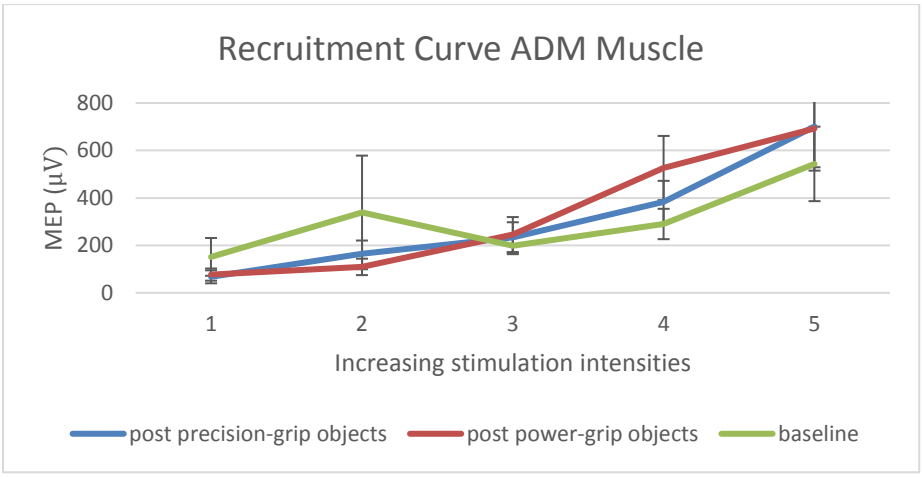
Figure 7.1. Input/output recruitment curves for (A) FDI muscle and (B) ADM muscle after each intervention. Error bars denote standard errors.

There was a significant interaction between muscle and intensity $F(4, 20) = 5.227$; $p = .005$, $\eta p^2 = .511$ but as the a priori interest was not to compare MEPs between muscles but to observe MEPs for each muscle after each type of intervention, this was not followed-up. Indeed, as can be seen from the y-axes scales in Figure 7.1, as predicted, due to normal use of this muscle (although non-significant), the FDI always produced much larger MEPs than those from the ADM, which together with variance in MEP size across stimulation intensities, produced the interaction.

Neither intervention produced significant differences of MEP size from either muscle relative to the other intervention, but, overall, MEPs were slightly larger for both muscles after viewing power-grip objects. For completeness, a post hoc 2x3x5 ANOVA included baseline results but produced no significant differences between baseline and either intervention (Figure 7.2). Being a pilot study with few participants (N = 6) this may account for the baseline MEP size that appears anomalous at the second intensity for the ADM muscle.



(A)



(B)

Figure 7.2. Input/output recruitment curves for (A) FDI muscle and (B) ADM muscle at baseline and after each intervention. Error bars denote standard errors.

Due to the non-significance of the group-average results, for completeness separate post hoc (2x3x5) ANOVAs were carried out for each participant, utilising the multiple MEPs recorded for each cell of the design. These were muscle by intervention (including baseline) by intensity ANOVAs. The primary interest was how muscle was affected by each intervention (so other results are not reported):

Subject 1 muscle x intervention interaction $F(2, 28) = 7.021$; $p = .012$, $\eta p^2 = .334$. Pairwise follow-ups showed that MEPs were for both muscles significantly larger at baseline than after interventions. For the FDI muscle $p = .011$ post FDI and $p < .001$ for post ADM. For the ADM muscle $p < .001$ after both interventions. There were no significant MEP differences between interventions.

Subject 2 muscle x intervention interaction not significant ($p = .350$).

Subject 3 muscle x intervention interaction $F(2, 28) = 14.355$; $p < .001$, $\eta p^2 = .506$. For FDI, MEPs were greater after each intervention compared to baseline; $p = .001$ for post FDI and $p < .001$ for post ADM. For ADM, post ADM MEPs were significantly greater than baseline; $p = .027$.

Subject 4 muscle x intervention interaction $F(2, 28) = 22.209$; $p < .001$, $\eta p^2 = .613$. For FDI, MEPs for both interventions were significantly greater than baseline MEPs; $p < .001$ for both. Also, for FDI, post ADM MEPs were significantly larger than those post FDI; $p = .003$. For ADM post FDI MEPs were significantly larger than baseline MEPs with $p = .007$ and post ADM means

were also significantly larger than baseline with $p < .001$. For ADM there were no significant differences between the two interventions.

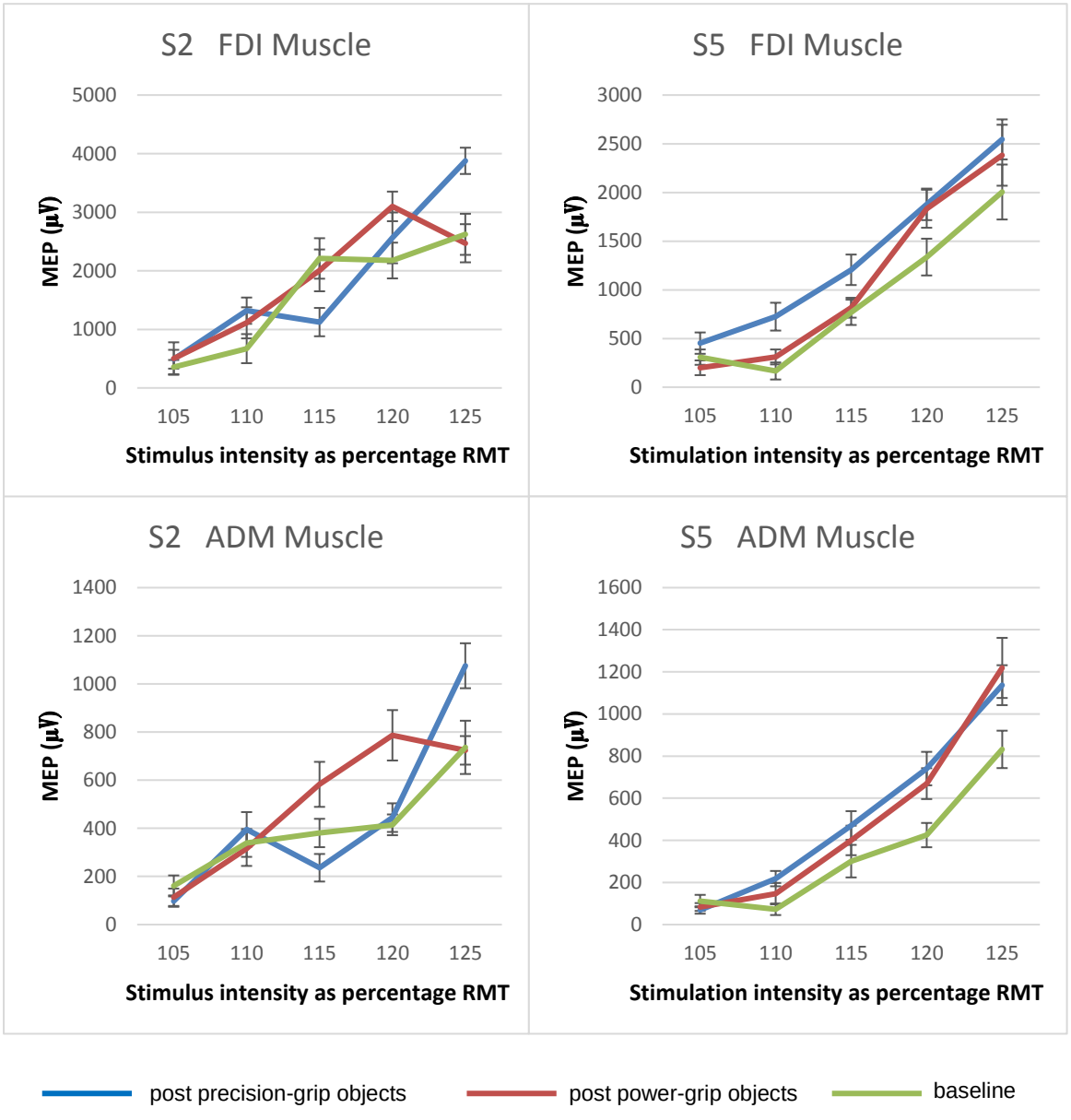


Figure 7.3. Upper boxes show results prior to and after each intervention for FDI muscle for Subject 2 (left side) and Subject 5 (right side). Lower boxes show results for ADM muscle for these two participants. Error bars denote standard errors.

Subject 5 muscle x intervention interaction $F(2, 28) = 5.936$; $p = .007$, $\eta p^2 = .298$. For FDI, MEPs were significantly greater post FDI compared to baseline, $p = .001$ and also significantly greater post FDI compared to post ADM, $p = .028$. For ADM, MEPs showed significantly greater means after each intervention compared to baseline, post FDI $p < .001$ and post ADM $p = .019$. There were no significant MEP differences between each intervention.

Subject 6 muscle x intervention interaction not significant ($p = .728$).

Examples of recruitment curves at the extremes of results are shown in Figure 7.3.

7.6 Discussion

If affordances evoked by passive viewing of stimuli are sufficient to lead to corticospinal changes in healthy subjects then repetitive viewing may be worth incorporating into therapeutic interventions after brain injury. To begin testing this theory TMS recruitment curves at increasing stimulation intensities were recorded from the right hand FDI and ADM muscles of 6 healthy volunteers. Each individual's RMT was obtained and then 15 TMS pulses were delivered at 105% RMT and repeated in 5% increments up to 125% RMT. Baseline MEPs were recorded (this ensured that increasing intensities were well tolerated) and then participants viewed 3D pictures of either precision-grip objects (Intervention 1) or power-grip objects (Intervention 2). Intensity mapping was repeated and the alternative intervention implemented followed by a further

intensity mapping. Results showed that neither intervention significantly modulated corticospinal activity.

7.6.1 Limitations - Current Experiment

An obvious limitation here was sample size. Consistency and size of MEPs varied hugely between subjects and also within-subjects at each separate intensity. Interestingly, the interventions often produced a similar pattern in the MEPs for both muscles; clearly observed for Subject 2. Here the power grip objects normally associated with the ADM produced greater MEPs on each muscle until the highest intensity where, for both muscles, the precision grip objects produced larger MEPs. By contrast, the shape of the curve from Subject 5 was generally what had been expected. Here, following presentation of the FDI, precision grip objects produced significantly larger MEPs than the power grip objects. However, this was the only participant-level data that had significant results in the expected direction. Hence these data showed little promise for motivating a larger study.

As in this pilot study, some researchers keep stimulation intensities to relatively low percentages. For example van de Ruit and Grey (2016) stimulated up to 130% RMT and up to120% active motor threshold (AMT) with participant's muscle contraction at 5-10% of their own maximal voluntary contraction (MVC) and then again at 10-40% MVC. Stern et al. (2016) were more conservative with up to 120% RMT for both their patient groups and control group.

Other researchers stimulate from subthreshold to saturation to create sigmoidal recruitment curves (Carson et al., 2013; Devanne et al., 1997; Talelli,

Waddingham, et al., 2008). Minimum and maximum stimulation intensities vary greatly; from 95% to 140% RMT (Carson et al., 2013) and from 90% to 180% RMT (Goldsworthy et al., 2016) to between 90% and 170% (AMT) with participant muscle contraction at 10-15% of their own maximal voluntary contraction (MVC) (Talelli, Waddingham et al., 2008). Stimulating at high intensity and thus causing MEP amplitude to saturate can be beneficial, for example, as mentioned above, Goldsworthy et al. (2016) observed inhibition of MEPs caused by cTBS only at intensities ≥ 150% RMT, where the upper part of the curve tended to saturate. For the purposes of the current experiment, it was believed that sufficient data would be derived from mid-range intensities but results may have been more conclusive if MEPs were obtained at >125% RMT, as the upper end of the curves in S2 suggest in Figure 7.3. However, for the two participants whose RMT were 56 and 64 very high intensities, e.g. 180% RMT would have been beyond the stimulator's capability. Moreover, as a pilot study it was deemed unnecessary to stimulate subthreshold as MEPs are not easily observed and, for participant comfort, to stimulate only up to 125% RMT (stimulating at high intensities can evoke facial muscle twitches and temporary scalp discomfort (Rossi et al., 2009).

A further limitation was the total "training time" of approximately 10 minutes passive viewing for each intervention. Significant results were obtained by Christiansen et al. (2017) where healthy individuals were trained in a visuomotor task, but training there consisting of 18 sessions of 28 minutes each. However, maintaining participant-task engagement is difficult when no verbal or motor response is required. To ensure alertness, the viewing time was limited to 8 minutes per intervention here, allowing incorporation of an extra 2

minutes' viewing between the different intensities of stimulation. This time constraint was felt necessary, as to maintain alertness with longer viewing times would require incorporating rest breaks, thereby possibly diminishing any affordance effects already created. Presumably, any long-term changes would represent the accumulation of shorter-term (session-by-session) changes; as attempted to capture here.

7.6.2 Limitations – Previous Experiments

The ideal cohort would have been stroke survivors attempting to make congruent hand movements while viewing the different types of objects. But as ethical approval would not have been forthcoming for this lab to carry out TMS on neurologically damaged individuals, the pilot study was designed for a healthy cohort, who had to be prevented from undertaking any movement in order to assess whether affordances alone might have some effect. The lack of increased MEPs from each muscle after passively viewing objects congruent for that muscle is therefore not entirely surprising. In fact, even passive *movement* caused by a mechanical device may not be effective (Jang et al., 2004; McDonnell et al., 2015).

Jang et al. (2004) observed activation of primary sensori-motor area (SM1), across precentral and postcentral gyri, during passive hand movements. Contralateral SM1 was activated in healthy controls undergoing fMRI when passive movements were made with their right hand. Then 17 hemiplegic patients were recruited within 4 weeks of stroke, all with a paretic hand motor index (MI) score of 0 (no movement) to undergo fMRI scanning. 12 patients were assigned to receive passive movements on wrist and finger joints to

activate SM1 (Group A). One session of 6 x 15s epochs of passive movement was carried out at a rate of 1Hz. The other 5 patients received no such treatment (Group B). MI scores were obtained three and six months later. Of Group A, after 6 months only 1 patient still had MI score of 0. The remaining had scores 1 to 4 and the 3 patients with the score of 4 also had significant motor improvements. Of Group B, after 6 months 3 still hade MI score of 0 and the other 2 had a score of 1.

Although there were differences in MI scores between the two groups, they did not reach statistical significance. The researchers suggested that such activation of sensori-motor areas by passive movement may have value relating the overall motor control network. While this may be true, the report did not mention how much other therapy, e.g. physiotherapy, mental imagery, action observation, any of the patients received during the 6 month period between the first and final MI assessments. The duration and number of sessions could have greatly affected results.

More recently, and similar to the current study, in an attempt to find methods translatable to stroke rehabilitation, McDonnell et al. (2015) investigated the primary motor cortex with TMS measures from 13 healthy, right-handed adults. Targeting the abductor pollicis brevis (APB) which is activated similarly to FDI, they identified RMT, MEP amplitude at a specified intensity and also mapped cortical area and volume. They investigated whether continuous passive motion (CPM) could induce a lasting increase in cortical representation of the thumb area. Thirty-minute sessions of variable amplitude and frequency of motion generated in the thumb were carried out over 3 consecutive days. TMS

measures were taken after each session and again 8 days after the last session. There were no significant differences in RMT, MEP amplitude or cortical area or volume following any of the CPM sessions or 8 days after cessation of the intervention.

Both Jang et al. (2004) and McDonnell et al. (2015) attempted to facilitate cortical reorganisation through passive movements. Similarly to the current experiment with passive viewing, results showed that these methods were unsuccessful in effecting cortical changes. Of course, in a true therapeutic setting viewing would not be deliberately passive; the object is a cue for action. During stroke rehabilitation patients would be expected to attempt movement of the affected hand when offered objects, so then the question arises whether incorporating attempted voluntary movement into the current study during the object viewing sessions would alter results?

7.7 Conclusion

Residual upper limb deficits caused by stroke impact activities of daily living so any therapy to improve patient outcomes is worth investigating. Therefore the pilot study was designed for healthy control subjects to determine whether repeated viewing of objects affording different types of grip response can enhance activity in the corticospinal tract. Mapping TMS intensities after passive viewing has not been reported before. From this novel approach, if such an effect could be shown in a healthy cohort then the viewing procedure could be adapted and incorporated into patient trials. TMS intensity mapping between 105% and 125% participant's own RMT was carried out at the beginning of the

session. It was repeated after participants viewed precision-grip objects which, when held, require movement of the FDI muscle and also repeated after viewing power-grip objects which would require movement of the ADM muscle. Input/output recruitment curves revealed large variations between MEP amplitudes across participants. Even in individual data differences in MEP amplitudes for 15 pulses delivered at a single intensity were sizeable. Resulting curves were not significantly different after the two viewing interventions, nor between the baseline and either intervention.

As a pilot study, even though results were non-significant, modifications could be made to the methods, such as increasing the range of stimulation intensities, length of training and/or number of pulses or incorporating a motor task. If any methodical differences enabled measurable changes in corticospinal activity from passive viewing then this would be worth investigating further with stroke patients.

Chapter 8

General Summary

Affordance effects have been researched for around 40 years but still relatively little is known of the time-course of this motor priming. One of the main aims of this thesis was to address this gap in current knowledge by providing pure scientific advances in the field of stimulus-evoked motor planning. The excellent temporal properties of TMS and EEG offer insight into neural activity within milliseconds of stimulus onset, so these methods were employed to record such activity while participants passively viewed manipulable objects. New information has been obtained to show that positioning objects close to the dominant hand can influence automatic motor planning.

The second main aim was to consider how affordance activity may be utilized in stroke recovery. Although affordances are being recognized as a tool in rehabilitation, as yet, there appears to be little or no literature relating to their time-course in therapeutic interventions. As part of the thesis, recruitment of stroke survivors with remaining loss of upper limb function has increased knowledge of their brain activity and provided greater understanding of the temporal nature of affordances after stroke.

In this chapter the key findings and conclusions from each of the experimental chapters are summarised, limitations of the experiments are considered, and the broader implications of the research and directions for future investigations are discussed.

8.1 Summary of Studies

8.1.1 Chapter 3

EEG study to detect affordance activity in healthy participants

The first EEG experiment investigated the time-course question via ERP components associated with affordance activity, particularly with the dominant hand closer to objects. Unlike previous experiments, stimuli were photographs viewed through a 3D stereoscopic viewer. Objects were categorized as affording a finger and thumb precision grip (e.g. tweezers, button) or affording a whole hand power grip (e.g. hairbrush, mug) and photographed on a desk with no lateral bias so that any handle was centrally positioned. In addition, there was also a 'no object' category, being a photograph of the empty desk. The study complemented and extended the work of Proverbio et al. 2011 whose categories were tools and non-tools. Their tools category was more varied and included some that were not entirely manipulable, e.g. a bicycle and a staircase.

As well as purely manipulable objects, for the new experiment a novel manipulation of posture was incorporated. Results revealed significant N2 ERP component differences at around 300ms after stimulus onset when either type of object was observed compared to no object. More robust evidence of affordance activity was the occurrence of different hemispheric activity. When right-handed participants adopted a posture with their dominant hand forward (closer to objects viewed in 3D) there was significantly more N2 negativity in the left hemisphere than when they adopted the posture with the left hand forward. However, the reverse was not evident in the right hemisphere when the left

hand was forward. Adding to current knowledge, this provided stronger evidence that the enhancement of the N2 occurring in response to objects that afford actions really represents the preparation of an appropriate action.

8.1.2 Chapter 4

TMS study to detect affordance activity in healthy participants

In this TMS study the intention was to expand on these EEG findings by observing the amplitudes of MEPs for TMS pulses delivered at different time-points while participants viewed objects. The plan was to examine corticospinal measures of motor activity and relate these to the EEG results. Similar posture manipulation and 3D stimulus presentation methods were adopted with precision-grip or power-grip objects. However, in both postures MEPs for the FDI were not significantly different when, congruent with use of that muscle, precision grip objects were presented compared to power grip objects. Likewise, no significant differences were apparent for MEPs from the ADM muscles whether precision- or power-grip objects were presented. Also, contrary to predictions, MEPs elicited in the dominant right hand forward posture were not significantly larger than those with the left hand forward.

8.1.3. Chapter 5

Investigating precision/power grip affordances via response times

Although strong results indicating affordances were obtained from the EEG experiment, the lack of ability to substantiate these with TMS led to the question of how effective viewing a stimulus in 3D might be compared to viewing it in 2D. Previously, TMS experiments had been carried out at the same laboratory but without the posture manipulation, and shown increased MEPs for object/muscle congruency (Makris et al., 2011, 2013). Stimuli were 2D objects (2011) and physical objects (2013).

Therefore a stimulus response compatibility experiment was designed with both 2D and 3D viewing of the same photographs of objects. Participants pressed a button using a precision or power grip depending on the change in background colour of the photograph and not in relation to the usual grip of that object. Results proved somewhat ambiguous. Contrary to previous results (Makris et al., 2011, 2013) responses congruent for the stimulus were not significantly faster than incongruent responses. Posture had no significant effect on RTs while, overall, viewing in 2D produced faster RTs than viewing in 3D. Precision grip responses were significantly faster than power grip responses.

8.1.4 Chapter 6

Investigating affordance activity in stroke survivors: An EEG experiment

Results from the first EEG experiment with young neurologically healthy adults suggested that the N2 ERP component was an indicator of neural activity associated with affordances and that having the dominant hand closest to the viewed objects modulated this activity. Therefore, despite being unable to provide supporting evidence from corticospinal or behavioural measures, an experiment was designed to discover if similar EEG results were evident in stroke survivors with loss of upper limb and hand function. Age-matched control subjects were also recruited. An overall goal with this project was to attempt to find how affordances, particularly in relation to their timing, might aid stroke rehabilitation. So with an aim to identify possible speeds at which to view repeated stimuli during rehabilitation, two presentation rates were incorporated into this study.

An early effect was detected at anterior electrodes between 100ms and 180ms after stimulus onset. When stimuli were presented at 0.5Hz rate (R1) (so viewed for 1s with a 1s interstimulus interval) results revealed significantly greater amplitude anterior N1 ERP components for each of the object categories compared to the empty desk. At the 1Hz (R2) rate (each stimulus viewed for 0.5s with 0.5s interstimulus interval) the precision-grip objects produced greater amplitudes than either other category. Although not as convincing at this presentation rate, the latter result suggested that differences were motoric rather than visual, as visual differences were more dramatic when viewing large

objects (for power grip) compared to small objects (for precision grip) yet the opposite pattern was observed in the anterior N1.

The N2 ERP component revealed continuation of this motor priming effect up to around 370ms after stimulus onset. For this component the slower R1 condition produced significantly larger N2 amplitudes than R2 and the object categories both produced significantly larger amplitudes than the no object category. Of particular interest was how similar the stroke survivor group results were to the age-matched neurologically healthy group. A brief investigation into the source of this cortical N2 activity was carried out on healthy control data by performing posture by hemisphere by stimulus category (2x2x3) ANOVAs for several regions of interest (ROIs). They were chosen in relation to investigations by Proverbio et al. (2011) and to reflect dorsal and ventral stream processing. There was no effect of posture but the left hemisphere had significantly more activity than right for the majority of ROIs. Both object categories were significantly more active than the no object category in all but one ROI where just power grip objects showed significantly more activity than the empty desk. Localising the source of neural activity is best achieved with fMRI, but nevertheless, these results broadly confirmed and extended those of Proverbio et al. (2011) showing probable left hemisphere dorsal stream motor processing.

The time scales for the generation of an affordance are in agreement with previous studies (e.g. Allami et al., 2014; Franca et al., 2012) and the similarity of stroke group and control group results leads to the suggestion of the occurrence post-stroke of largely automatic motoric brain activity attributable to the properties of objects. The fact that there was no significant interaction

between presentation rates and stimulus categories infers that either rate could be adopted in a therapeutic setting. However, only the slower rate revealed significant differences between each of the object categories and the no object category for the early anterior N1 component. Therefore, it may be advantageous to encourage any available benefit from early motoric processing by using the slower, 0.5Hz rate rather than increasing the number of presentations with the faster, 1Hz presentation rate.

8.1.5 Chapter 7

Piloting affordances as therapy: Cortical plasticity in healthy controls

An aim of the thesis was to suggest a possible method of incorporating affordance-related motor priming into stroke rehabilitation to improve patient outcomes. To investigate whether repeated passive viewing of objects could effect corticospinal changes, a TMS intensity mapping paradigm was employed for a pilot study. Right hand FDI and ADM were monitored with EMG as TMS pulses were delivered at 105% rising to 125% of individual participant RMT. There were two interventions; one was viewing a repetition of precision-grip objects and the other a repetition of power-grip objects. After each separate intervention the TMS intensity mapping was performed. Being a purely passive activity, with the TMS being delivered after each viewing, results were expected to be subtle, but it was hoped that recruitment curves showing some congruency between muscle and power/precision grip objects would be achieved. In fact, there were no significant effects for congruency. As a pilot study it provided a starting point for variations in method that could possibly

lead to repeated object viewing being trialled in stroke therapy, but the benefits of such an intervention remain speculative.

8.2 Practical and Theoretical Implications

Based on the literature review in Chapter 1, two main areas of investigation were outlined. First, after an object appears in view how soon does an affordance occur and how soon does it dissipate? Secondly, is affordance activity after stroke the same as in neurologically healthy people and, if so, how can this be used in stroke rehabilitation?

8.2.1 Time-course of Affordances

J. J. Gibson first fully introduced the term 'affordance' in his seminal work "The Theory of Affordances" in 1977 and related it to everything in our environment from surfaces underfoot to the medium of air and to all substances, animals and persons around us. The expression has since been commonly used to define the relationship of an object's intrinsic features with an observer's repertoire of actions. Integrated perceptual, cognitive and motor functions are engaged by properties of the object, creating a variety of possible interactions. So, what is the typical time-course of such affordances? Exactly when do they start and how long can they be sustained? These are the questions driving this project.

Previously, object stimuli have been presented in 2D (Allami et al., 2014; Buccino et al., 2009; Grèzes et al., 2003; Makris et al., 2011; Proverbio et al., 2011; Proverbio et al., 2013; Tucker and Ellis, 1998, 2004; Valyear et al., 2007)

or as physical objects (Franca et al., 2012; Makris et al., 2013; Tucker & Ellis, 2001) and even as computer generated objects (e.g. Cardellicchio et al., 2011). Introducing and removing physical objects is laborious (for both scientific experiments and potential therapy) so a novel feature of the experimental approach throughout this project was the use of 3D pictures. Photographs were taken with a 3D camera and presented to subjects on a computer screen observed through a stereoscopic viewer. This enabled presentation of objects as realistically as possible at speeds that could be engineered by computer software. Thus, from stimulus presentation, precision could be maintained in monitoring the millisecond timing of neural activity by EEG and corticospinal reactions from TMS pulses as well as recording behavioural responses.

A further novel aspect was the introduction of a posture manipulation. Again, in previous research either handle orientation was not an experimental factor (Grèzes et al., 2003; Proverbio et al., 2011; Tucker and Ellis, 2004; Valyear et al., 2007) or position of object handles was modulated (Goslin et al., 2012; McNair et al., 2017; Tucker and Ellis, 1998) or objects deliberately presented to avoid lateral bias (Creem-Regehr & Lee, 2005; Franca et al., 2012; Makris et al., 2011). Throughout this project, posture modulation was incorporated by positioning the dominant or non-dominant hand close to the computer monitor and consequently, closer to the objects being observed.

Proximity, or spatial coding, may be separable from object affordances. Cho and Proctor (2010) argued that Simon-based affordance effects were not due to object affordance but to the location of a handle. In a study with comparatively similar design but contrary to the findings of Tucker and Ellis (1998), their

participants' within-hand responses were similar to between-hand responses, indicating that lateral proximity of object to hand was irrelevant. Wilf et al. (2013) also reported dissociation between affordance and spatial compatibility effects although, as recorded in Chapter 3, this spatial compatibility only related to laterality without distinguishing between distal and proximal objects. Many more studies have maintained that a handle is an intrinsic property of an object and therefore part of an affordance effect (e.g. Bub, et al., 2018; Goslin et al., 2012; Grèzes and Decety, 2002; McNair et al., 2017; Phillips and Ward, 2002; Symes et al., 2007).

However, motor priming by affordances *should* be influenced by our ability to interact with the object. Response times for paired-object behavioural studies indicate that faster responses are made when related compared to unrelated objects are correctly positioned (Roux-Sibilon, Kalénine, Pichat, & Peyrin, 2018; Xu et al., 2015; Yoon, Humphreys, & Riddoch, 2010). Responses are faster if the 'active' object, e.g. jug of water compared to 'passive' empty glass, is correctly positioned for action, but not affected by changing the position of the passive object (Xu et al., 2015). When hands are viewed holding the pairs of objects, response speed is increased if viewed in first person compared to third person perspective (Yoon et al., 2010). Further, for correctly-positioned related pairs of objects, when a hand appears functionally ready to act, responses are faster compared to when there is no hand present or when it is resting passively or incorrectly positioned for action (Borghi, Flumini, Natraj, & Wheaton, 2012).

Combining the novel posture modulation with action priming in the current experiments was intended to extend previous research and to produce more

compelling evidence of affordances. The (additional) requirement that any putative affordance effect should be enhanced when it is easier to interact with an object sets a higher evidential bar. For the putative affordance effects investigated here, this bar was not always cleared. Indeed, in the presence of this manipulation, the more established effects that were being built upon were sometimes not observed at all.

The first TMS experiment compared MEP responses from the right hand FDI and ADM hand muscles while right-handed participants viewed 3D stimuli of precision-grip and power-grip objects. The stimuli were the same photographs of objects as in the first EEG experiment. It revealed that TMS pulses delivered earlier (within 300ms of stimulus onset) rather than later produced larger MEPs but, unfortunately, as muscle/object congruent MEPS were not significantly larger, did not provide clear confirmation of affordances. Nor did the posture modulation significantly affect the results.

However, with the same stimuli but incorporating a photograph of the empty desk as a ‘no object’ category, the EEG experiment provided evidence that brain activity was modulated by positioning the dominant hand closer to objects appearing in 3D.

Proverbio et al. (2011) had reported early motoric activity from 210ms after stimulus onset in the form of enhanced N2 peak for tools compared to other, non-tool objects. The current study refined the stimuli by maintaining the same desk and background in all photographs and compared manipulable objects which required specific types of grip against each other and both against a

stimulus with the desk and background lacking an object. The current study revealed an earlier negative-going N1 peak in activity between 100ms and 200ms after stimulus onset.

Another methodological difference to Proverbio et al. (2011) was that their EEG consisted of 128 electrodes. For their anterior recordings relating to N2 ERP components electrodes AF3, AF4, AFP3h and AFP4h were selected. The closest corresponding electrodes in the 64 electrode system in place at the City, University of London laboratory were identified as F1 in the left hemisphere and F2 in the right hemisphere.

For the N2 peak in the left (dominant) hemisphere there was a posture x stimulus interaction which revealed that when the right (dominant) hand was positioned nearer to the monitor there were enhanced differences between object categories as well as between no object and both object categories. This suggested new evidence that placing objects close to the dominant hand produced greater affordance effects.

From the anterior N1 and N2 results, the intrinsic properties of objects appear to be initiating motoric neural activity as early as 100ms after stimulus onset, developing over the time-course of the following 260ms. Previous EEG research showed lateralized readiness potentials at around 100ms but this occurred as participants prepared to make a physical response (Goslin et al., 2012; Vogel and Luck, 2000). This may be the first EEG recording of such early object-evoked motor-related brain activity resulting from purely *passive* object viewing.

As mentioned above, the 3D stimuli were an important part of these investigations and so the original set of photographs were rated for their suitability. Raters viewed each object photograph through the 3D viewer for a few seconds but without a time restriction and made conscious decisions about the type of grip they would use for each object. This was a necessity to be able to separate objects into the two categories; precision-grip and power-grip. The second set of raters viewed them to make a conscious decision for familiarity, also without a time limit. Combining the results, objects with the highest rating were selected for the first EEG and TMS experiments, together with the 'no object' empty desk photograph.

The N1 and N2 results from the EEG study indicated that the objects, that had been consciously rated did, indeed, also produce automatic motor priming. However, as the first TMS experiment and subsequent behavioural study produced inconclusive results, adhering strictly to the idea that the highest rated objects would produce the strongest affordance-effects may not have been correct. Therefore, in the second EEG experiment some objects were chosen from slightly lower conscious ratings but perhaps had equal, or better, intrinsic properties. For example, the sweet in a plastic and foil wrapper may 'afford' an action because of its visual properties and/or due to the goal-driven aspect of pleasure from taste.

Comparisons between the N1 and N2 component results in the two experiments (Figure 3.2 on page 85 and Figure 6.1 on page 162) indicate that perhaps the second set of objects produced better automatic priming as here the object

categories produced generally slightly greater negative peaks compared to the no object category. However, it could also be the case that fewer in number, i.e. 6 objects in the second compared to 10 in the first experiment, improved the priming effect.

The EEG and TMS experiments (Chapters 3 and 4) were designed to determine the full time-course over which affordance effects are available. As alluded to briefly in the second EEG experiment source analysis, the cortical potentials stem from a variety of, mostly dorsal-stream, neuronal populations. This activity differs considerably to any MEP congruency effect as TMS pulses produce the far more specific corticospinal activation. Therefore to the extent that affordances are modulated by posture (which, in itself, is far from proven) the N2 peaks probably result from general manual motoric activation, which would be unobservable in a comparison that always includes manipulable objects, such as the TMS and Response Time studies.

With the exception of Proverbio et al. (2011) who found affordance effects as late as 600ms after stimulus onset, EEG results of motor-evoked brain activity while passively viewing objects were in line with previous findings (e.g. Franca et al., 2012; Makris et al., 2011, 2013).

8.2.2 Affordance Activity after Stroke

Motor priming identified in young healthy control subjects from the EEG experiment prompted a similar investigation with stroke survivors. Motivated by

the possibility that such motor priming might be incoporated in rehabiliation regimes, chronic stage stroke survivors with remaining upper limb deficits were recruited along with age-matched control participants.

The EEG paradigm differed from the earlier experiment in two ways. As mentioned above, some objects were changed. Stimuli were limited to three instead of six in each object category to allow incorporation of two separate presentation rates without prolonging the experiment. This was important due to the possibility that some stroke survivors might suffer from fatigue and not be able to tolerate a long experiment. As before, the empty desk ‘no object’ category was included.

The second main difference was that there were two presentation rates. Establishing the optimum observation time, and the best repetition rate to enhance motoric activity in stroke survivors could be valuable. Already there are a number of virtual realtity (VR) stroke interventions (Alankus et al., 2010; Burke et al., 2009; Crosbie et al., 2008; Morrow et al., 2006; Saposnik et al., 2010; Standen et al., 2015) but, as yet, the time-course of affordances has not been a factor in these programs. In a bid to strengthen rehabilitative therapies, knowledge of the length of time an affordance is active within the brain could help inform timed object re-introduction within such VR programs.

In other respects, the design was similar to the previous EEG and TMS experiments with the two posture modulations and a stereoscopic viewer used to produce stimuli in three dimensions (3D). Both N1 and N2 ERP components were investigated but here, as the site of lesion may affect such components, a

further consideration was to detect the source of the N2 activity. Due to limitations of the BrainVision software and lacking specific knowledge of lesion location for the stroke survivors, this was carried out only on the data of the age-matched control group.

Results for N1 and N2 were broadly similar to the earlier study. Visual inspection of inidividual data revealed peak latencies to be, generally, slightly later with the exception of posterior N1 being 100ms to 200ms, the same as for the younger adults and anterior N1 being earlier, between 100ms and 180ms. The P2 peak occurred between 180ms and 260ms compared to between160ms and 260ms and the N2 peak occurred between 280ms and 370ms compared to between 235ms and 360ms. The posterior N1 results differed slightly as, here, there was a difference between the two object categories. However, given the fact that there were no differences between the no-object category and either object category it would appear that both types of object were visually processed in a similar manner as the empty desk. The anterior N1 result in the faster presentation rate (1Hz) mirrored that of the earlier study with precision-grip objects producing significantly larger N1 activity than the empty desk. Interestingly, in the slower (0.5Hz) presentation rate there were significant differences between categories with significantly greater N1activity for each object category compared to the empty desk, perhaps advancing the previous experiment's indication of early motoric activity.

The posture manipulation from the earlier experiment with young adults which revealed greater left hemispheric activity in the right hand forward posture was not reproducible. While it would have provided more robust evidence of

affordances, it is also the case that increasing age reduces hemispheric asymmetry (Cabeza, 2002; Graziadio et al., 2015; Ward & Frackowiak, 2003; Wu & Hallett, 2005). Although handle orientation, rather than posture modulation, played a part in many earlier studies (e.g. Bub et al., 2018; Buccino et al., 2009; Grèzes and Decety, 2002; Symes et al., 2007; Tucker and Ellis, 1998), these all recruited only young volunteers. In particular, greater left hemispheric activity was reported when tools were observed compared to non-tools (Proverbio et al., 2011) and with handles orientated towards the right (dominant) hand (Proverbio et al., 2013). Perhaps this result would be different with older age participants.

However, for the N2 peak in the current study significant differences were revealed between each of the object categories and the no object category, suggesting motoric activity. As shown previously in Figure 6.1 on page 162 this was the case for both stroke survivors and the age-matched neurologically healthy participants. The slower, 0.5Hz presentation rate produced signficantly larger N2 peaks than the faster, 1Hz rate, so the LORETA source analysis was conducted on the 0.5Hz rate and, as this was the posture of most interest, only for the right hand forward posture.

Overall, results revealed significantly greater magnitudes of current densites in dorsal stream regions of interest when objects were viewed compared to the empty desk. Engagement of such areas, related to visual guidance for movement, would suggest that automatic motoric activity was produced by the object stimuli.

To gain benefit from any automatically ocurring object affordances in VR programs, the results suggest that viewing time and re-introduction of objects to enhance early motor priming should be at a rate no faster than 0.5Hz. However, an alternative interpretation is that increasing the number of times objects are viewed by a faster repitition speed could increase to opportunity of creating new affordances.

On the premise of the former, the TMS pilot study was undertaken to ascertain whether repetitive viewing of manipulable objects at this rate could facilitate cortical projections to FDI and ADM muscles in a persistent manner. However, training time was short and with a very small number of participants significant results were not forthcoming.

8.3 Experimental Limitations

8.3.1 EEG Experiments

Both of the EEG experiments produced new information regarding affordances. The posture manipulation in the first experiment was innotvative in showing stronger automatic motor priming when the dominant hand is positioned close to an object.

In the second experiment, due to software limitiations, source analysis identifying areas of neuronal activity could not be carried out on the stroke survivor group. Without precise knowledge of site of lesion, affordance-related activity can only be assumed to occur either from undamaged tissue and/or

through neuro-plastic changes. However, the current source density maps do not locate the neuronal source, so there is no inverse problem to solve, but they do show the voltage potential differences recorded across the scalp. These maps were very similar in the N2 time-window for both chronic stage stroke survivors who had remaining loss of upper limb function and neurologically healthy age-matched participants, showing particularly negative voltages when objects were viewed. Maps for the right hand forward posture at the presentation rate of 0.5Hz are shown in Figure 8.1.

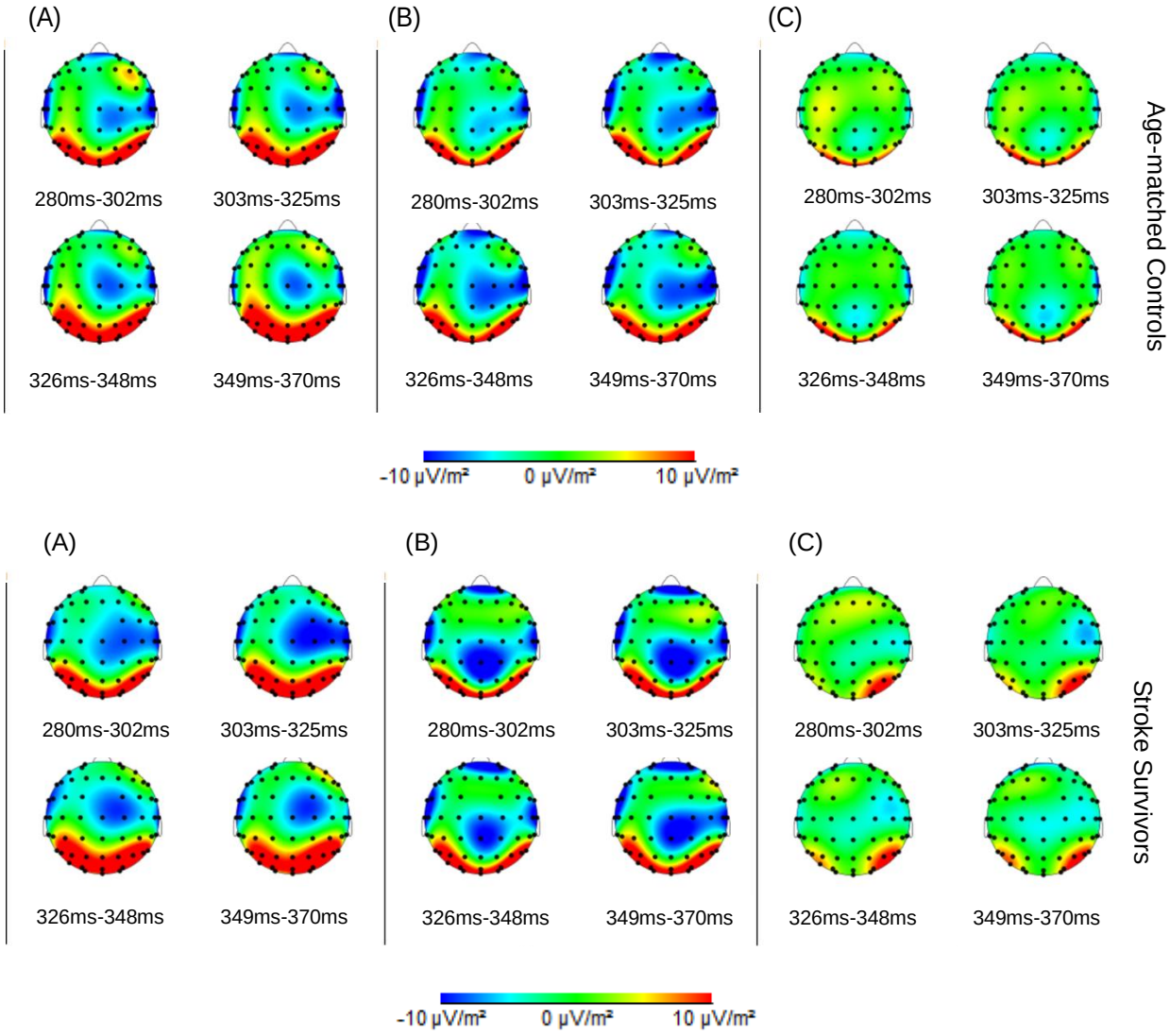


Figure 8.1. Current source density maps for Control Group (top) and Stroke Group (bottom) over the time-course of the N2 peak. Head maps in (A), (B) and (C) relate to the different stimulus categories; (A) power-grip objects, (B) precision-grip objects, (C) empty desk.

This suggests new evidence that affordance-related activity remains, even when the hand is not fully functional. Cortical reorganization is paramount in stroke recovery and, even when the dominant hand of neuroligically healthy participants is immobilized, short-term cortical changes can occur (Avanzino, Bassolino, Pozzo, & Bove, 2011; Bassolino, Bove, Jacono, Fadiga, & Pozzo, 2012; Kühn et al., 2014). An fMRI investigation by Kühn et al. (2014) required participants to passively view objects once without immobilization and once with their right (dominant) hand immobilized. On each occasion the same objects were viewed twice, once for handle orientation towards the left and once towards the right. During immobilization functional reorganization took place, notably with greater activation of right hemispheric premotor cortex when handles were orientated towards the left. The authors concluded that even short-term immobilization can cause rapid changes in neural processing of affordances from the visual perception of objects. Certainly, the stroke survivors who took part in the EEG experiment showed similar affordance-related activity to the controls. But using fMRI to ascertain differences in activity between subjects and possibly revealing the extent of cortical plasticity would be hugely beneficial in the investigation of affordances.

The most obvious limitation in the current project is that stroke survivors had different degrees of hand mobility and none had a diagnosis of apraxia. The value of incorporating regimes attempting to enhance affordance activity in rehabiliation therapies may only be truly measured once affordance-related brain activity can be established in apraxic patients.

8.3.2 TMS Experiments

The design of the first TMS experiment to determine affordance activity in healthy controls was expected to show some muscle/object congruency effects. As these were not forthcoming, it is possible that viewing through the stereoscopic viewer while having TMS pulses delivered increased the load on cognitive resources and consequently reduced automatic motoric information processing.

The attempt to briefly alter corticospinal activity throughout the second experiment by repetitive object viewing prior to intensity mapping may have been unsuccessful due to the extemely limited training time. As discussed in Chapter 7, this was a pilot study and other metholodical changes, such as incorporating a motor task, as well as an increased number of participants may produce more effective results.

8.3.3 General Limitations

Throughout this project the aim was to produce conditions close to representing those in stroke rehabilitation settings. For example, adopting different posture positions shared simlarities to the positioning of objects on patients' neglected side when encouraging vision and movement to that side. In most rehabilitation settings, physical objects are used to cue movement but for methodolical purposes the studies needed precision timing. Viewing objects in three dimensions while being able to engineer the speed of their presentation was achieved by the photographs and the stereoscopic viewer. However, in some

instances, the physical properties of the viewer itself may have become a distraction; particularly when administering TMS pulses. The behavioural response time experiment also indicated that the three dimensional viewing system was no more beneficial in producing congruent grip responses to 'pinchable' and 'graspable' objects than viewing two dimensional photographs. Possibly the best way to remedy this so that presentation rates could be maintained would be to produce objects in contextual scenarios in the virtual reality platform. For example, the garden trowel in a garden setting and the hairbrush on a dressing table with a mirror.

8.4 Future Directions

Ideally, EEG experiments similar to those carried out in this project but recruiting patients who have a diagnosis of apraxia could provide better information regarding benefits of incorporating affordance effects in rehabilition therapies. Comparisons could also be made between brain activity of patients in the acute stage with those in chronic stage.

Choice of object and manner of presentation are probably the key points to be considered. Although automatic affordances should require no conscious appraisal of an object's properties, aesthetically pleasing objects may enhance affordance effects. Righi et al. (2014) provided pictures of objects functionally varying affordance and attractiveness. EEG results revealed greater affordance effects for objects regarded has having the strongest affordance *and* attractive properties. However this, itself, would need further investigation as the research group requested participants to make conscious decisions about the objects'

properties during the EEG recording, possibly introducing bias into the results. Another consideration is that high resolution, realistic graphics for virtual objects in virtual settings might be the simplest and yet major contribution to improved research paradigms and possibly to future rehabilitation interventions.

Conclusion

This research has provided the first comprehensive indication of the length of time that affordance effects occur in healthy controls and in chronic-phase stroke patients. The EEG experiments have contributed to knowledge of motor system priming by specifically looking at the temporal nature of affordance relating to hand motor actions. It has been shown that positioning the dominant hand close to objects produces strong affordance effects.

This is also the first research to consider that due to the motor effects of affordances, a time limit on object viewing but repetitive re-introduction of objects may be beneficial in a therapeutic setting.

Appendices

APPENDIX A

TMS medical screening questionnaire

Please answer all questions carefully, and ask for clarification if you are unsure.

1. Have you ever had a seizure, convulsion, fit or a blackout? Y / N
2. Does anyone in your extended family (i.e. siblings, parents, grandparents, aunts, uncles, cousins etc.) have epilepsy? Y / N
3. Have you ever had a stroke? Y / N
4. Have you ever had a serious head injury or neurosurgery? Y / N
5. Have you ever had any other brain-related condition, including neurological or psychiatric illnesses? Y / N
6. Have you ever had any illness that caused brain injury? Y / N
7. Do you have any metal in your head (outside of your mouth) such as shrapnel, surgical clips, or fragments from welding/metalwork? Y / N
8. Do you have any implanted devices such as cardiac pacemakers, medical pumps or intracardiac lines? Y / N
9. Do you suffer from frequent or severe headaches? Y / N
10. Are you taking any medication aside from the contraceptive pill? Y / N
11. Could you be pregnant? Y / N
12. Do you have a tendency to faint? Y / N
13. Do you have a heavy goods vehicle driving license, pilot's license or bus license? Y / N
14. Do you suffer from anxiety symptoms / panic attacks Y / N

We would additionally advise that you DO NOT undertake the study if:

- You feel unwell today
- You have a temperature
- You have a serious medical condition
- You did not get a good night's sleep last night
- You have consumed alcohol today, or had more than one drink last night
- You have consumed more caffeine today than you usually would

- You have recently used recreational drugs

15. Do any of these conditions apply to you? Y / N

TO BE COMPLETED BY ALL PARTICIPANTS PRIOR TO TESTING. IF ANY QUESTION IS ANSWERED POSITIVELY THE PARTICIPANT SHOULD NOT BE TESTED.

Name (print):…….

Signed:…….Date:…….

APPENDIX B

Post-TMS participant feedback form

Please take a few moments to complete this form, which will help us compile accurate statistics regarding any adverse reactions to TMS.

Name (block capitals):

Age:

TO BE COMPLETED BY THE EXPERIMENTER

1) Please describe the parameters of the TMS protocol employed, and whether the experiment was completed:

2) Was there any evidence that the TMS protocol provoked, or came close to provoking, a seizure of any kind? If so please describe:

TO BE COMPLETED BY THE PARTICIPANT

3) Would you agree with the answer to question 2 provided by the experimenter? Y / N

If not, please elaborate (you may continue overleaf):

PLEASE TURN OVER

4) Did receiving TMS cause you to experience:

a) Pain or discomfort as a result of muscular twitching? None / Mild / Severe

b) Headache? None / Mild / Severe

c) Anxiety? None / Mild / Severe

Please elaborate, and also describe any other symptoms you experienced, in your own words:

Signed (experimenter):……Date:……...

Signed (participant):……....Date:……...

APPENDIX C

Standardized Mini-Mental State Examination

DIRECTIONS FOR ADMINISTRATION OF THE SMMSE

1. Before the questionnaire is administered, try to get the person to sit down facing you. Assess the person's ability to hear and understand very simple conversation, e.g. *What is your name?* If the person uses hearing or visual aids, provide these before starting.
2. Introduce yourself and try to get the person's confidence. Before you begin, get the person's permission to ask questions, e.g. *Would it be all right to ask you some questions about your memory?* This helps to avoid catastrophic reactions.
3. Ask each question a maximum of three times. If the subject does not respond, score 0.
4. If the person answers incorrectly, score 0. Accept that answer and do not ask The question again, hint or provide any physical clues such as head shaking, etc.
5. The following equipment is required to administer the instrument: A watch, a pencil, Page 2 of this SMMSE with CLOSE YOUR EYES written in large letters and two five-sided figures intersecting to make a four-sided figure, and Page 3, a blank piece of paper.
6. If the person answers "What did you say?" Do not explain or engage in conversation. Merely repeat the same directions a maximum of three times.
7. If the person interrupts (e.g. What is this for?), just reply: *I will explain in a few minutes when we are finished. Now if we could proceed please….we are almost finished.*

1. (Allow 10 seconds for each reply)
a) What year is this? (accept exact answer only) **/1**
b) What season is this? (during the last week of the old season or first week of a new season, accept either). **/1**
c) What month is this? (on the first day of a new month or last day of the previous month, accept either). **/1**
d) What is today's date? (accept previous or next date) **/1**
e) What day of the week is this? (accept exact answer only) **/1**
2. (Allow 10 seconds for each reply)
a) What country are we in? (accept exact answer only) **/1**
b) What city/town are we in? (accept exact answer only) **/1**
c) What area of London are we in? (accept Islington, Angel or City) **/1**
d) What is the name of this building? (accept Rhind or City University) **/1**
3. Say*:* *I am going to name three objects. When I am finished, I want you to repeat them. Remember what they are because I am going To ask you to name them again in a few minutes.* (say slowly at approximately one-second intervals) **/3**

Ball Car Man

(For repeated use: Bell, jar, fan; Bill, tar, can; Bull, bar, pan)
Please repeat the three items for me. (score one point for each correct reply on the first attempt) Allow 20 seconds for reply; if the person did not repeat all three, repeat until they are learned or up to a maximum of five times. (but only score first attempt)
4. Spell the word WORLD. (you may help the person to spell the word correctly) Say: *Now spell it backwards please*. **/5**
(allow 30 seconds; if the subject cannot spell world even with

assistance, score 0) Refer to following page for scoring instructions

5. Say: *Now what were the three objects I asked you to remember?* **/3**
(score one point for each correct answer regardless of order; allow 10 seconds)

6. Show wristwatch. *Ask: What is this called?* **/1**
(score one point for correct response; accept "wristwatch" or "watch"; do not accept "clock" or " time" , etc.; allow 10 seconds)

7. Show pencil. *Ask: What is this called?* **/1**
(score one point for correct response; accept "pencil" only; score 0 for pen; allow 10 seconds for reply)

8. Say: *I would like you to repeat a phrase after me: No ifs, ands, or buts* **/1**
(allow 10 seconds for response. Score one point for a correct repetition. Must be exact, e.g. no ifs or buts, score 0)

9. Say*: Read the words on this page and then do what it says* **/3**
Then, hand the person the sheet with CLOSE YOUR EYES on it. If the Subject Just reads and does not close eyes, you may repeat: *Read the words on this page and then do what it says,* (a maximum of three times. This is covered in#3 directions section above). Allow 10 seconds, score one point only if the subject closes eyes. The subject does not have to read aloud.

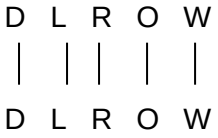
10. Hand the person a pencil and paper (Page 3). Say: *Write any complete sentence on that piece of paper.* Allow 30 seconds. Score one point. The sentence must make sense. Ignore spelling errors. **/1**

11. Place design, pencil, eraser and paper in front of the person. Say: *Copy this design please.* Allow multiple tries. Wait until the person is Finished and hands it back. Score one point for a correctly copied diagram. The person must have drawn a four-sided figure between two five-sided figures. Maximum time: One minute. **/1**

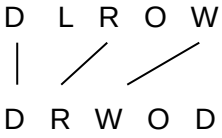
12. Ask the person if s/he is right or left handed. Take a piece of paper, hold it up in front of the person and say the following: *Take this paper in your right/left hand* (whichever is non-dominant), *fold the paper in half once with both hands and put the paper down on the floor.* Allow 30 seconds. **/3**

TOTAL SCORE /30

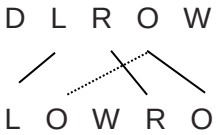
Scoring WORLD backwards (scoring instructions for item #4)
Write the person's response below the correct response.
Draw lines matching the same letters in the correct response and the Response given. These lines MUST NOT cross each other.
The person's score is the maximum number of lines that can be drawn without crossing any. Examples:



scores 5



scores 3



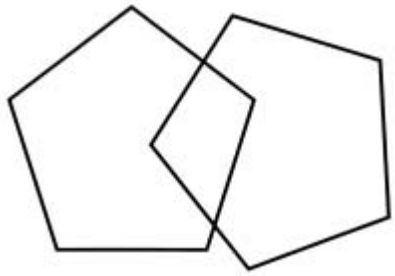
scores 3

scores 1

scores 3

scores 0

Close Your Eyes



Item 10: Sentence Writing

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